# NAVAL POSTGRADUATE SCHOOL

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# THESIS

**TEMPERATURE STABILIZATION FOR NEGATIVE BIAS TEMPERATURE INSTABILITY**

by

Brian K. Harbison

September 2007

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**13. ABSTRACT (maximum 200 words)**

Previous research was conducted on a Complementary Metal Oxide Semiconductor (CMOS) to determine the impact of a phenomenon known as Negative Bias Temperature Instability (NBTI). NBTI affects the operational characteristics of these devices, with a stronger effect on p-channel devices. This instability is apparent when the semiconductor is 'on' biased, and exacerbated under thermal stress. This data is useful in determining the projected failure rate of certain submicron technologies. The previous experiment used On-the-Fly techniques at certain temperatures to measure the interface states in order to determine the susceptibility of the device under test to NBTI. In the previous research, thermal stress application was not exact. Temperature drift was observed over long range test evaluations, and subsequent NBTI data was determined unsatisfactory. In order to maintain thermal stress at a constant value during NBTI testing temperature stabilization is necessary. This paper explains the methods explored and adapted to stabilize temperature.

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# TEMPERATURE STABILIZATION FOR NEGATIVE BIAS TEMPERATURE INSTABILITY

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requirements for the degree of

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# ABSTRACT

Previous research was conducted on a Complementary Metal Oxide Semiconductor (CMOS) to determine the impact of a phenomenon known as Negative Bias Temperature Instability (NBTI). NBTI affects the operational characteristics of these devices, with a stronger effect on p-channel devices. This instability is apparent when the semiconductor is ‘on’ biased, and exacerbated under thermal stress. Previous research used On-the-Fly techniques at certain temperatures to measure the interface states in order to determine the susceptibility of the device to NBTI. This data is useful in determining the projected failure rate of certain submicron technologies. During the previous experiment temperature drift was observed over long range test evaluations, and subsequent data determined unsatisfactory due to the change in thermal stress. In order to provide test data at specific temperatures, temperature stabilization is necessary to maintain constant thermal stress during data collection. This paper explains the methods explored and adapted to stabilize specific testing temperature.

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# EXECUTIVE SUMMARY

In microelectronic components, Negative Bias Temperature Instability (NBTI) is a phenomenon that affects PMOS devices and degrades their performance. NBTI occurs due to a lattice mismatch between the bulk silicon and the gate oxide which leads to the creation of dangling bonds. Acting as charge traps, these bonds can change the operating characteristics of the device. Normally these bonds are rendered passive with the introduction of hydrogen during the fabrication process. Under an electric field or a thermal stress hydrogen can disassociate and diffuse away from the bonds, changing the operating characteristics of the device. This is a concern because the device characteristics will change as the threshold voltage shifts. Over an extended and undetermined period of time under stress the device could be rendered inoperative, causing functional failures in microelectric circuits.

Previous testing was performed in an attempt to quantify the amount of degradation observed over a period of time. This testing was conducted on a specially fabricated test bed under specific thermal conditions. A fixed amount of current through an embedded heater was used to provide the thermal stress desired. However, it was noted that over longer testing periods (three or more hours of testing) the heater resistance drifted which caused a change in the applied thermal stress. This change in thermal stress affected the testing in progress and skewed the data. The subsequent results gathered did not support earlier work from other experiments and produced conclusions and were in conflict with previous research in the field.

In order to ensure a constant thermal stress is applied for the duration of future testing a feedback solution is necessary for temperature stabilization. Current feedback and correction during data collection will ensure test conditions remain static during each experiment. The data collected under constant thermal

conditions could then be analyzed to determine NBTI failure rates, or at the very least would assist in identifying other problem areas in the experiment.

This testing is necessary because of the impact the results will have on military use of microelectronic components. Successful NBTI experiments could assist in predicting failure rates for microelectronic components. As the military is dependent on commercial technology which is affected by NBTI, failure rates will help determine susceptibility of components in current use in military applications. Because commercial data is not available when these components are operated under higher stress conditions, this testing would provide a benchmark to gage component failure for a variety of applications in current military inventory.

# I. INTRODUCTION

## A. RESEARCH OBJECTIVE

The goal of this research is to find a way to stabilize temperature while conducting On-the-Fly measurements on Complementary Metal Oxide Semiconductor (CMOS) devices from the IBM Trusted Foundry 130nm process designed for military applications. In previous research, data was gathered from a p-channel Metal-Oxide Semiconductor (PMOS) transistor test structure developed by the Air Force Research Laboratories (AFRL). Testing was performed to gather data in order to determine structure degradation under various thermal stresses. The data gathered from the On-the-Fly measurement technique was collected at specific temperatures to determine the effects under various thermal stress conditions. Unfortunately, over testing periods of more than three hours in length temperatures drifted up to a degree from original values and rendered the subsequent data misleading when predicting degradation under controlled thermal conditions. With feedback incorporated into the thermal stress mechanism, temperatures can be held relatively constant (to within +/- 0.05 of one degree), ensuring data collected is not adversely affected by a temperature change over the course of the test.

## B. BACKGROUND

The previous research in this area was conducted by Ensign Christopher Schuster in conjunction with a project from the AFRL using a test structure specifically designed for the purpose of reliability testing. The primary motivation for this testing is the special interest held by the military in reliability and availability.

## 1. DoD Issues

The Department of Defense (DoD) has very specific reliability requirements for microelectronic components, and off-the-shelf technology generally does not meet DoD specifications. Recent shifts in the semiconductor market provided the DoD with almost no component availability. With this lower availability the DoD was forced to consider alternate solutions to meet the continuing need for technical components.

### *a. Military Background and Concerns*

Previously in the military stock system, standards for qualified parts were specified with military standards. Microcircuitry standards were outlined in MIL-STD-883E which specified "…suitable for use within Military and Aerospace electronic systems including basic environmental tests to determine resistance to deleterious effects of natural elements and conditions surrounding military and space operations…" [1]. However, the DoD had increasing difficulty procuring qualified and tested parts from manufacturers as the microelectronic market shifted to meet increasing consumer demand. Figure 1 shows the shift in the semiconductor market in the previous few decades.

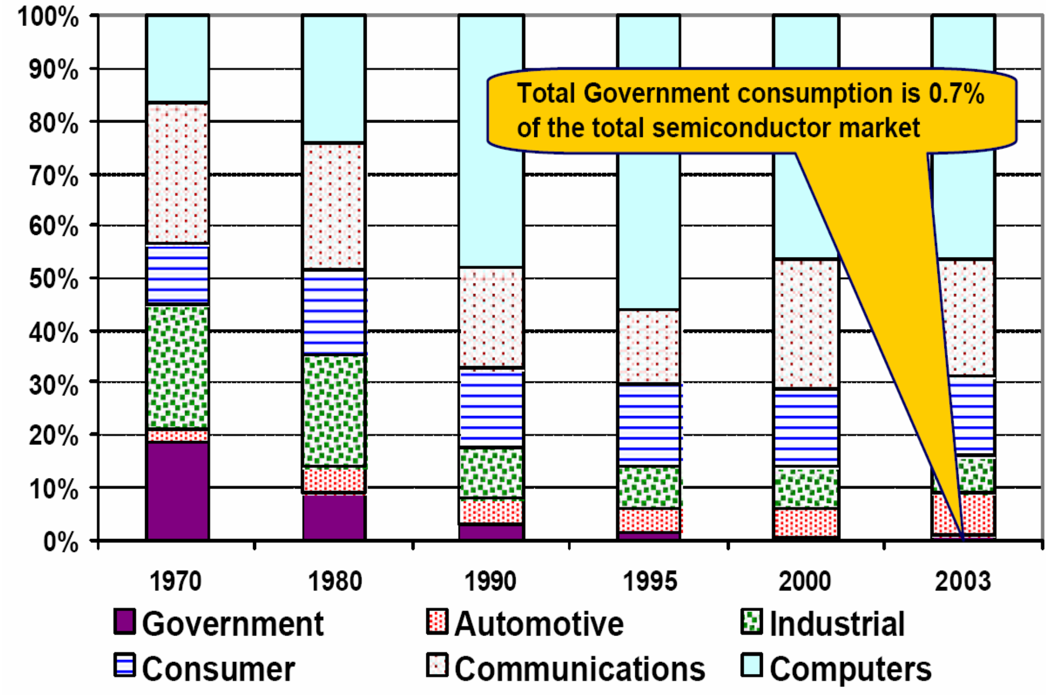



**Figure 1. Recent Market Shifts [From 2].**

Today, a current estimate from the Defense Science Board puts DoD consumption at about one to two percent of the entire global supply [3]. A second, but equally worrisome issue is supply reliability. With manufacturing processes moving to off-shore locations in order to cut costs [3], fabrication facilities in the continental United States are becoming limited. This fact poses two important concerns. First, the possibility of supply interruption is increased, especially in the event of a conflict (armed or otherwise) with the manufacturing nation. Second, the likelihood of compromised electronics increases [3] as fabrication proceeds in locations that have a greater availability to outside tampering.

### *b. Possible Solutions*

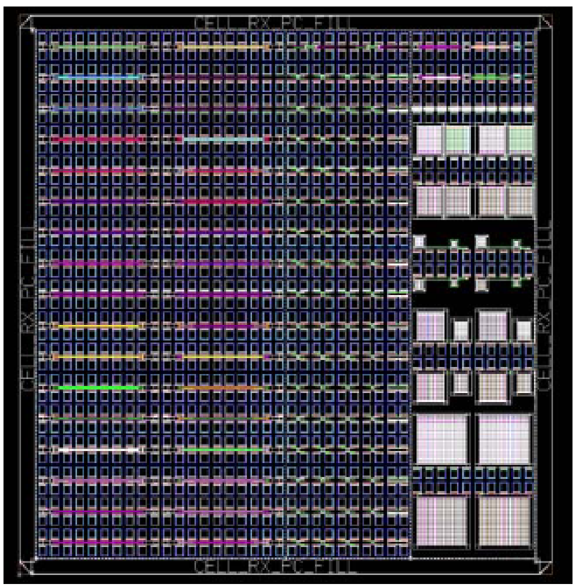
In response to the above concerns, the government explored options for the continued fabrication of reliable microelectronic components. Proposals for a consolidated DoD semiconductor foundry [2, 4] were considered, but opponents cited the high cost and the likely negative influence on existing American industry [4]. While a long term solution was being considered by the Defense Science Board, a short term solution was proposed that would make use of continental semiconductor manufacturers. The Defense Trusted Integrated Circuits Strategy (DTICS) was proposed by Deputy Secretary Wolfowitz in 2003, and the Trusted Affairs Programs Office (TAPO) was formed. Working with International Business Machine (IBM) a business relationship was forged to produce 'trusted' microelectronics. The first step in this process was the use of an IBM facility in Vermont, with the possibility of more to come. This relationship allowed the DoD to use IBM facilities to manufacture the most current microelectronics, but these components were not guaranteed to meet any military requirements [5].

## 2. AFRL Test Structure

With the above agreement in effect, the military obviously needed a method to test existing microelectronic components in order to determine failure rates and responses under adverse conditions not normally experienced by commercial products. One possible testing method was to produce a structure comparable to modern technologies that would be available for testing. The AFRL working with Sandia Technologies manufactured the test structure that was used in the previous thesis work. The structure was comprehensively designed to incorporate a variety of experiments, one of which was NBTI effects. In order to provide data that could be applied to trusted foundry components, the test structure was assembled using the same IBM process used in 130nm gate length CMOS fabrication.

### *a. Overview*

The unbound test die is shown in Figure 2. Approximately 5x5mm, testing is accomplished by bonding the die in a DIP package, or using probes placed directly on the die bond pads. The NBTI pads are located in the upper right half of the die [6]. The majority of the die is designed for other testing that has no impact on this work.




| | | | |
|---|---|---|---|
| EM_M3_p2u | EM_M4_p2u | NBTI | ILD_M4_M5_M6_COMB |
| EM_M8_3u | EM_PCONT | HC_D_P_HV_p24 | ILD_M1_M2_M3_COMB |
| EM_M8_p64u | EM_CONT_N_P | HC_D_N_HV_p24 | CAP_TRANS |
| EM_M7_3u | EM_V7_U | HC_C_P_HV_p24 | |
| EM_M7_p64u | EM_V7_L | HC_C_N_HV_p24 | CAP_FIA |
| EM_M6_3u | EM_V6_U | HC_B_P_HV_p24 | |
| EM_M6_p32u | EM_V6_L | HC_B_N_HV_p24 | |
| EM_M5_3u | EM_V5_U | HC_A_P_HV_p24 | CAP_A_SMALL |
| EM_M5_p32u | EM_V5_L | HC_A_N_HV_p24 | |
| EM_M4_3u | EM_V4_U | HC_D_P_LV_p12 | |
| EM_M4_p32u | EM_V4_L | HC_D_N_LV_p12 | CAP_A_MIDDLE |
| EM_M3_3u | EM_V3_U | HC_C_P_LV_p12 | |
| EM_M3_p32u | EM_V3_L | HC_C_N_LV_p12 | |
| EM_M2_3u | EM_V2_U | HC_B_P_LV_p12 | |
| EM_M2_p32u | EM_V2_L | HC_B_N_LV_p12 | CAP_A_BIG |
| EM_M1_3u | EM_V1_U | HC_A_P_LV_p12 | |
| EM_M1_p24u | EM_V1_L | HC_A_N_LV_p12 | |

**Figure 2. AFRL Test Structure [6, From 8].**

### *b. NBTI Structure*

The portion of the structure devoted to NBTI testing includes two PMOS devices, and each device has a thermistor and heater built directly beside. In order to increase accuracy in resistance measurements the thermistors have four bond pads instead of two (this is to facilitate a Kelvin connection). The additional two pads on the sensing lines have almost no resistance (only line resistance) and will give a more accurate measurement of

the voltage difference because there is far less current traveling through the sense lines than the force lines.  A schematic of the device is shown in Figure 3.

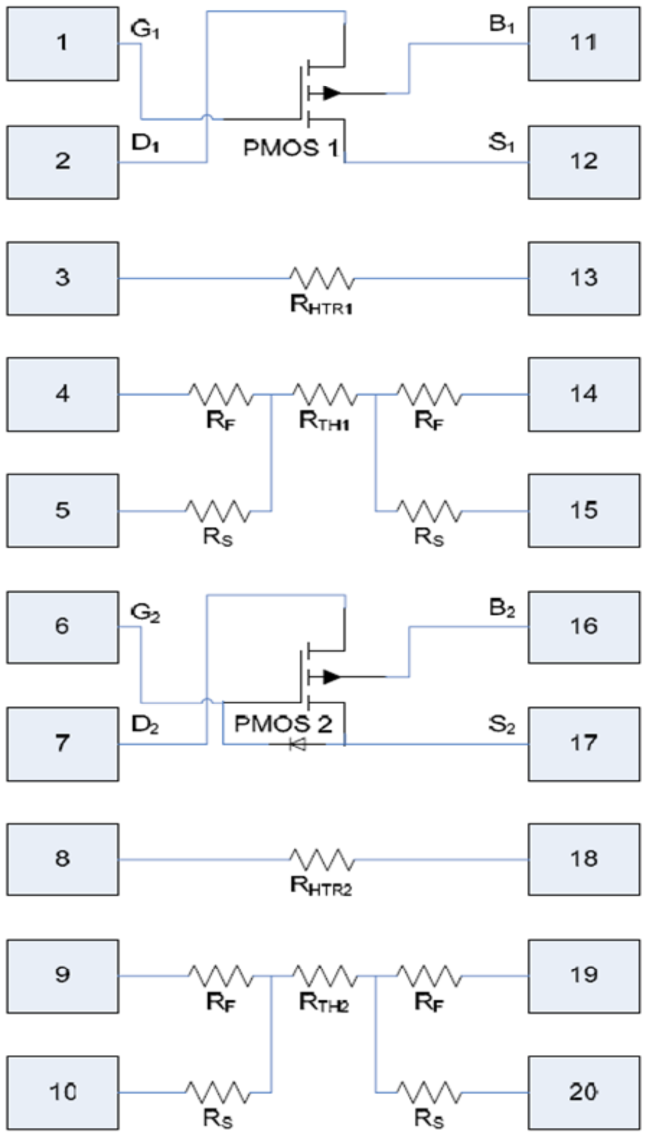



**Figure 3. AFRL Test Structure, NBTI Portion [From 8].**

The structure is a low voltage device that uses a supply voltage of 1.5V and gate voltage of approximately -2.2V [8].  Figure 4 summarizes the operating specifications for the IBM 130nm node.

| CMOS specifications (common to 130-nm technology platform) | |
|---|---|
| **Lithography** | 130 nm |
| **Voltage ($V_{DD}$)** | 1.2 V or 1.5 V |
| **Additional power supply options** | 2.5 V / 3.3 V I/O |
| **Standard NFET / PFET** | |
| $L_{min}$ | 0.12 μm |
| $L_{p}$ | 0.09 μm |
| $V_{tsat}$ | 0.355 V / -0.300 V |
| $I_{Dsat}$ | 530 μA/μm / 210 μA/μm |
| $I_{off}$ | 300 pA/μm / 350 pA/μm |
| $T_{ox}$ | 2.2 nm |

Note: Specifications given for 1.2 V (nominal) at 25°C.

**Figure 4. IBM Node Data for 130nm Process [From 7].**

The heater and thermistor are located adjacent to each transistor, as seen in Figure 3. Each heater has a resistance of approximately 20Ω. Thermistor resistance is calculated using the difference between the force and sense lines, and is measured to be approximately 22Ω (increased accuracy depends on the specific device under consideration) at 25°C [8].

## C. NEGATIVE BIAS TEMPERATURE INSTABILITY (NBTI)

When a bias is applied that places a PMOS device channel into inversion, NBTI can occur, shifting threshold voltage. The condition can be exacerbated with higher temperatures or voltages. Acting in a non-linear manner, the interference occurs on the molecular level where the silicon interfaces with the gate oxide. Device physical layout, fabrication process and interface procedures can also contribute to NBTI effects.

## 1. PMOS Overview

Rather than go into detail on PMOS operation, the following figures will summarize the important aspects of the devices. Figure 5 shows a generic p-channel device as well as the circuit schematic representation.

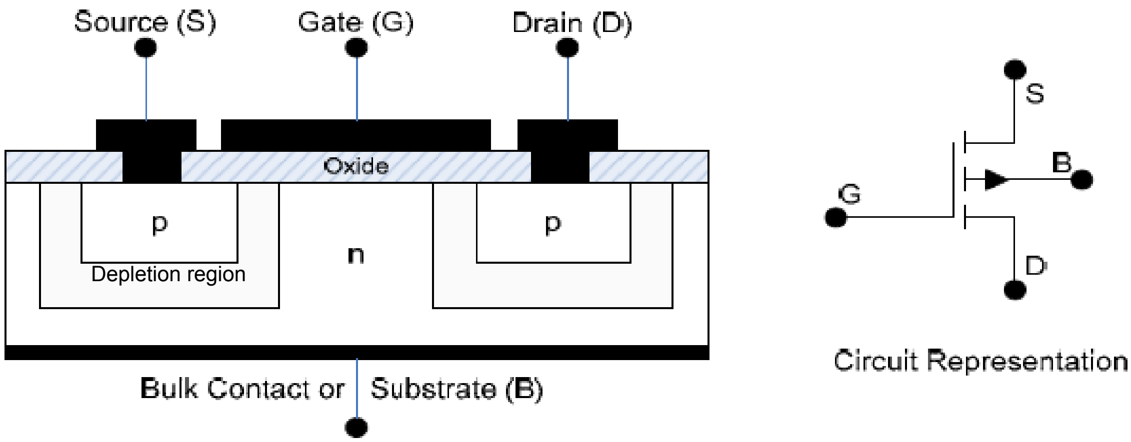



**Figure 5. Generic PMOS Cross Section and Schematic [After 9].**

Normally a differential voltage (gate voltage) across the 'Source' and 'Drain' connections will form a channel of charge carriers which will allow the current to flow: in effect, the PMOS device is acting like a switch. A threshold voltage ($V_{th}$) is the gate voltage above which drain current will flow. With different biases the devices will yield different results. This is because the device is operating in different regions: either the cutoff, triode or saturation regions [10]. These regions of operation dictate whether the device is conducting or not. A summary of the operating regions is shown in Figure 6. $V_{GS}$ is the Gate-Source voltage, $V_{DS}$ is the Drain-Source voltage, $V_{th}$ is the threshold voltage, and $I_{DS}$ is the Drain-Source current.

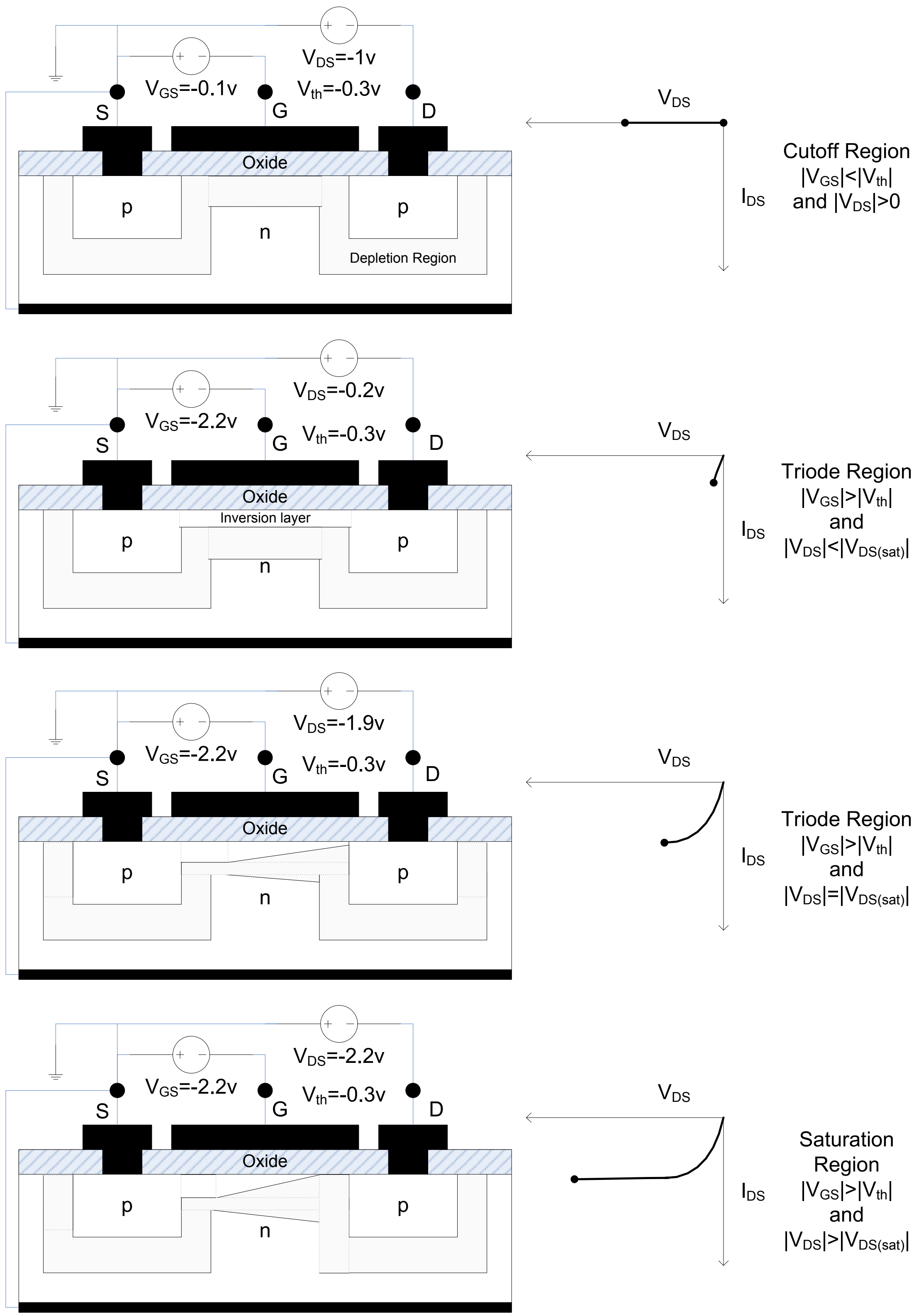



**Figure 6. PMOS Drain Current versus Drain-Source Voltage Biases [From 8, 9].**

## 2. NBTI Defect Origins

During the fabrication process, when the oxide is grown on the silicon crystal on a molecular level the interface is uneven and leaves traps (in the form of dangling silicon bonds) for either holes or electrons. During this fabrication technique hydrogen is also introduced and fills the traps as well as the other spaces in the device. Hydrogen then bonds with the extra dangling silicon bonds and renders the trap passive. Although the specific origins of NBTI are unknown, most experimental data supports a rise of instability due to a chemical reaction at the interface, allowing the hydrogen to diffuse through the oxide layer [6, 11]. This diffusion exposes traps at the interface, which then shift the threshold voltage for the device as more charge is lost to the traps. Voltage stress and temperature will vary the threshold voltage, but the baseline cause is the hydrogen diffusion.

During the fabrication process hydrogen can be generated. There are several theories whether this is neutral H, $H_2$ or $H^+$. When the stress is removed from the device there is a level of 'recuperation' that will shift threshold voltage back to the original value (where the rate of shifting is specific to the device and the previous stress). The hydrogen close to the interface sites will return to the trap location and once again render the traps passive, shifting the voltage required to bias the device back towards the original value [6, 11].

# II. SUMMARY OF PREVIOUS RESEARCH

## A. MEASUREMENT TECHNIQUES CONSIDERED

There are three different techniques considered in the previous research to gather the pertinent data on NBTI. The method used was the On-the-Fly measurement technique, but the Charge Pumping and Direct Threshold measurement techniques will be outlined as well.

### 1. On-the-Fly Measurement

This is a simple, widely used technique [12, 13] that biases the PMOS device to operate in the linear triode region at a pre-set stress temperature. The level of degradation is determined from the percentage change of the drain current, which is used to find threshold voltage change. Ease of measurement is the primary reason this method was used in previous thesis work.

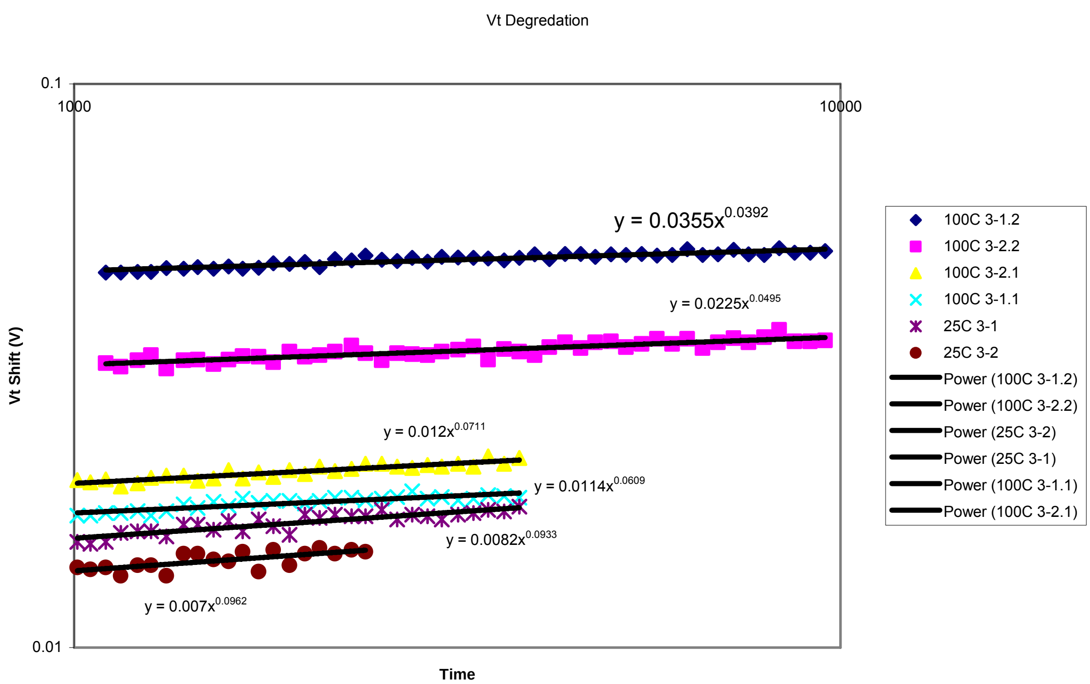



**Figure 7. Previous Findings for Threshold Voltage Shift [From 8].**

While this was the method used in previous research there are some drawbacks. On-the-Fly measurements have two primary disadvantages. First, this method does not provide any information about the instability mechanism or interface defect concentrations [12]. While a measurement of the amount of degradation is available, the method of degradation is unknown. Second, a metric related to the transconductance in the device called the process transconductance parameter ($k_p'$) [10] may not be constant. This parameter is the product of the mobility of electrons/holes and the capacitance per unit gate area, and is usually determined by the fabrication process and determined to be a constant of the device. If this factor is not constant the regions of device operation could shift from a linear operating region to an exponential region.

### 2. Charge Pumping and Direct Threshold Voltage Measurements

The Charge Pumping technique can provide information about the interface states in the devices. The advantage of this method is that it provides interface state data that can be directly interpreted as device degradation. The primary reason it was not used in the previous research was the delay between stress removal and charge pumping test could allow device relaxation which would produce erroneous results [11, 12, 13].

The Direct Threshold Voltage Measurement technique was presented at the 2006 IRPS conference [8, 14] and is advantageous in that the data is gathered very close (on the order of 10s of microseconds) to the time the stress is interrupted. This provides the ability to run tests on shorter stress time periods and the ability to measure threshold voltage directly. Due to the novelty of this technique and the lack of experienced history, this technique was not attempted.

## B. THERMISTOR AND HEATER USAGE

This research will focus on improving the previous technique used to control thermal stress. Rather than use a heat source external to the device under test, the integrated thermistor/heater combination was used to generate

the thermal stress. Additionally, thermistor and heater performance was not determined using p-n junction differences in diode current as an indication of device temperature. While this would be an accurate indication of the device's temperature, it was beyond the scope of the previous research. Thermistor and heater performance were determined by calibrating these devices to the output of a Micromanipulator Heat Control Module and Hot Chuck.

### 1. Baseline Theory

The premise of the calibration relies on the almost linear relationship between a material's resistance to current flow and the change in temperature. This property is not common to all materials, but metals, for the most part, have this relationship. The linear profile for the material can provide an indication of the devices resistance and correlating temperature. The value related to the specific slope for the material is the Temperature Coefficient of Resistivity (TCR) and is defined by the below equation [9]:

$$\alpha_0 = \frac{1}{\rho_0}\left[\frac{\delta\rho}{\delta T}\right]_{T=T_0} \tag{2.1}$$

The $\rho_0$ term is the reference temperature resistivity of the material. The partial derivative accounts for the change in resistivity with the change in temperature (from the reference resistivity to the resistivity under consideration). Equation 2.1 can be modified to a close linear approximation by removing the partial derivative:

$$\rho = \rho_0\left[1+\alpha_0\left(T-T_0\right)\right] \tag{2.2}$$

In order to use this approximation in an experimental application, the relationship between resistance and resistivity is used to further modify the equation. In order to make this assumption, the area and length of the resistor is taken to be constant.

$$R = R_0\left[1+\alpha_0\left(T-T_0\right)\right] \text{ where } \rho = \frac{RA}{L} \tag{2.3}$$

With equation 2.3 the TCR can now be experimentally determined simply by taking resistance measurements at known temperatures. The above equation can be used to correlate to a known heat source output—previous thesis work used a hot chuck to correlate the thermistor [8].

### 2. Overview and Procedure for AFRL Device

The setup used to determine the TCR experimentally is shown in Figure 8. The bare test die was placed on the hot chuck and heated to a constant temperature. Electrical connections are made to pads five and fifteen to measure resistance. Voltage is applied to the force connection (pads four and fourteen) and then measurements of differential voltage are taken from the sense pads. By dividing the sense line voltage with the force line current, the resistance of the thermistor is determined. The self-heating due to current application and dissipated energy not converted to thermal energy was deemed negligible [8]. After gathering data at different temperatures, a linear plot is generated to determine the TCR, and from this plot resistance can be calculated in order to give an indication of temperature. The assumption was made that different device thermistors would have the same TCR because they were made of the same material [8].

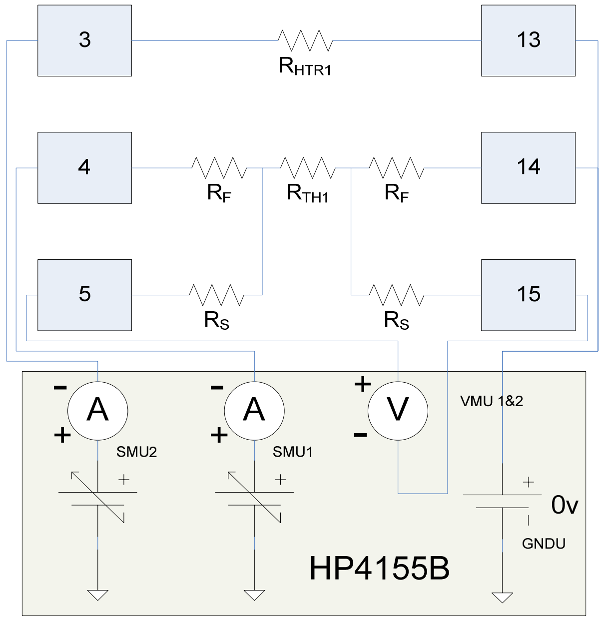



**Figure 8. Heater Test Circuit [From 8].**

## C. PREVIOUS RESULTS

Results from the previous thesis work are presented here with basic explanations on how the data was gathered and the interpreted meaning.

### 1. Heater and Thermistor Results

The TCR for the thermistor was determined from multiple test devices. With the TCR, the specific devices under consideration were measured to establish a baseline initial condition, with the dependence on temperature extrapolated by using the previously found TCR. The heater in the specific device was then biased to reach the temperature under consideration by using the thermistor readings to determine device temperature.

### a. *Thermistor Results*

Four test devices were used to find the TCR for the thermistor. The first die was measured at three temperatures and the other devices measured at two to verify correlation between the devices. The results are summarized in Table 1.

**Table 1. Resistance Measurements [From 8].**

| | Average Resistance (Ω) at Temperatures: | | | | |
|---|---|---|---|---|---|
| Device | **20°C** | **25°C** | **75°C** | **100°C** | TCR |
| A | 23.99 | - | 28.00 | 29.60 | 0.0029 |
| B | - | 23.84 | - | 29.34 | 0.0031 |
| C | - | 24.80 | - | 29.63 | 0.0026 |
| D | - | 24.55 | - | 29.60 | 0.0027 |
| Average | | 24.40 | | 29.54 | 0.0028 |

The data in Table 1 are averages. 315 second measurement periods were used after the hot chuck temperatures stabilized at the desired value. The data gathered (minus the first five seconds) was then averaged for the resistance values given. The average value for the thermistor TCR was used for the remainder of the experiment. With further calculations, the temperature variation between devices was determined to be on the order of 10% above or below the specific temperature desired (in degrees Celsius) [8].

### b. *Heater Bias Results*

With the above results for the thermistor, the heater in the device could then be biased to provide the desired thermal stress on the PMOS device. Bias voltages were less than two volts, and currents less than 0.1 amps. By stepping voltages from 0.0 to 1.75 volts in the heater, the thermistor resistances are recorded and then correlated to the approximate temperatures using the TCR. These approximate temperatures are recorded in Table 2. Table 3 is then

constructed using the temperatures from Table 2 and the TCR to find the required voltages through the heaters to produce a device temperature at 25, 75 and 100°C. The heater voltages, while not entirely accurate, should place the test device at approximately the desired temperature for testing.

**Table 2. Heater Bias and Resistance Measurements [From 8].**

| | Device A | | Device B | |
|---|---|---|---|---|
| $V_{HTR}$ (V) | R (Ω) | T (˚C) | R (Ω) | T (˚C) |
| 0.000 | 21.995 | 20.100 | 21.713 | 20.300 |
| 0.250 | 22.124 | 22.165 | 21.773 | 21.276 |
| 0.500 | 22.504 | 28.264 | 22.143 | 27.285 |
| 0.750 | 23.109 | 37.964 | 22.779 | 37.628 |
| 1.000 | 23.916 | 50.914 | 23.595 | 50.882 |
| 1.250 | 24.883 | 66.424 | 24.570 | 66.734 |
| 1.500 | 25.978 | 83.995 | 25.683 | 84.821 |
| 1.750 | 27.188 | 103.416 | 26.898 | 104.559 |

**Table 3. Heater Bias Results [From 8].**

| | Device A | | | Device B | | |
|---|---|---|---|---|---|---|
| T (˚C) | $P_{HTR}$ | $V_{HTR}$ | R (Ω) | $P_{HTR}$ | $V_{HTR}$ | R (Ω) |
| 25 | 0.009 | 0.381 | 22.301 | 0.008 | 0.363 | 22.002 |
| 75 | 0.089 | 1.418 | 25.417 | 0.083 | 1.369 | 25.079 |
| 100 | 0.129 | 1.739 | 26.975 | 0.121 | 1.680 | 26.617 |

### 2. Impact on Stress Measurements

The temperatures used to stress the PMOS devices in the previous research were 25°C and 100°C. At 100°C the tests were performed over periods of three and eight hours. To reach the desired temperatures a fixed bias was applied to the heater for the duration of the test. For the tests only data between 1000 and 10000 seconds was used because this was the region where the

heater current was stable enough to verify the temperature was within the desired range.  Figure 9 shows the device needed approximately 1000 seconds to stabilize and temperatures began to degrade at about 10000 seconds for the remainder of the tests.

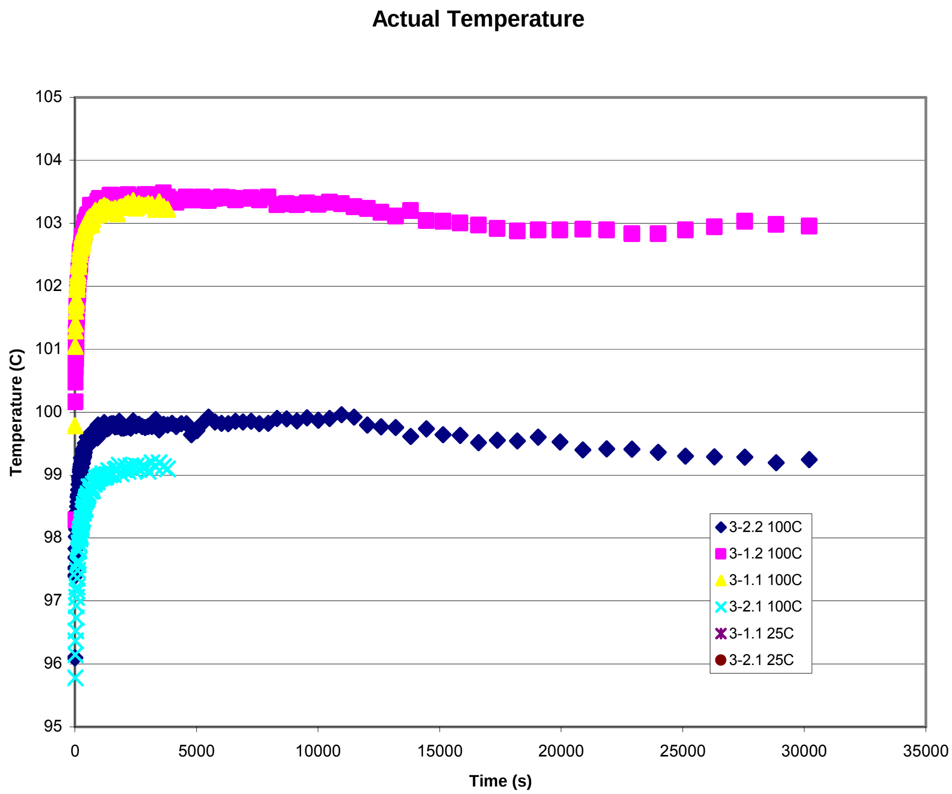



**Figure 9. Temperature Results [From 8].**

### 3. Heater Control Issues

From the above data there are two major issues with the heaters.  First, and less importantly, the exact temperature of the heaters needs to be confirmed with a more accurate method.  Using the TCR gives a good approximation of the temperature, but has too much margin for error to provide viable data at a specific temperature.  This issue is minimized in the scope of the experiment because the goal was to determine NBTI effects at a constant temperature: as

long as the temperature was constant, the temperature error would be applied over the scope of the testing and not impact the NBTI results. The second issue of heater control has more potential for larger experimental variation. With no way to control the temperature over the course of the experiment there was no guarantee the device was under the same thermal stress for the period of data collection. This would suggest data could have been taken under different thermal stresses, and the results would not accurately indicate the effects of NBTI under controlled conditions. It could have been for this reason previous data collected did not correlate with classical research.

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# III. SOLUTION THEORY

## A. CONTROL THEORY OVERVIEW

This section will address the general control theory required to maintain stability in a simple system. For the purposes of this experiment, it is assumed purely resistive electrical components (like the resistors in the AFRL test bed) do not exhibit any inductive or capacitive characteristics and store energy in no form.

### 1. System Analysis

The basic problem is the need to find a method to maintain the specific lattice temperature generated by the resistor constant for the duration of the testing. In previous research, the value of resistance (measured by differential voltage) was observed to fall over a long period of testing. The reason behind the decline in resistance is not addressed in this research. The issue is maintaining test temperature constant. In previous testing the temperature required was determined by using the temperature coefficient of resistivity to determine the required voltage drop across the resistor. With this value calculated, a constant current was then applied and the voltage drop measured to determine the experimental temperature. However, during the experiment the measured voltage did not remain constant, and no system was in place to return the voltage to the desired value to maintain the constant thermal stress required.

#### *a. Closed Loop Systems*

During testing where parameters of a system can change over the course of operation, closed loop feedback is desired to ensure the system is continually corrected to maintain the desired output. The advantage of a closed loop system is the signal output from the system of interest can be fed back into a comparator to continuously adjust the input. This continual adjustment will force

the system to achieve the desired output. Closed-loop configuration is less sensitive to disturbances and plant perturbation because of the incorporation of feedback within the plant [15]. Figure 10 shows a general closed-loop control system with the major components.

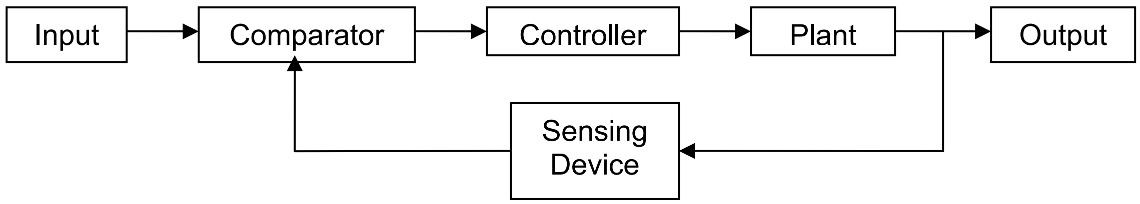


**Figure 10. General Closed Loop Control System.**

The input is a steady signal that is assumed to be constant for the duration of the time the plant is in operation. The comparator takes the combination of the input and the feedback from the sensing device and provides the difference between the two inputs to the controller. The controller accepts the signal and performs two general functions. First, the difference between the input and the feedback from the sensing device is applied to the signal before it enters the plant. Usually the sensing device output is applied as a form of negative feedback in order to keep the signal from increasing without bound or rapidly decreasing to zero. Second, a gain is added to the signal to ensure the input to the plant is appropriate for the plant to perform its designed function. When the signal comes from the plant it goes to the output where it can be analyzed and to the sensing device to feed back into the comparator. While the closed loop plant is generally more expensive than a plant with no feedback, it is most widely used in applications where plant variation or noise is expected.

#### *b. Theory Application*

To apply a closed loop system solution to a specific plant (where the term plant is used to describe the system under test) the type and order of

the system must be understood.  In many cases, the order of a plant system can be difficult to predict based on the actual plant.  A mathematical plant model or experimental results need to be analyzed to determine the order of the plant. Once the order has been determined, response to stimulation is observed to assist in predicting plant parameters.  When stimulation is applied to a plant the control engineer can measure a variety of indicators to determine plant parameters.  Time to rise to the final output, time to settle at the final output, percent overshoot, damping effects, and response time are all metrics used in plant analysis.  With data on these metrics available, the engineer can then determine the plant order and calculate the forced and natural responses to outside stimulus.  Finally, using this data, the control-loop can be applied or modified to change the plant forced response and achieve the desired response.

## B. SOLUTION FOR AFRL TEST BED

In the case of the AFRL test bed, a solution is necessary to maintain temperature constant for the duration of testing.  Previous experiments used both the heater and thermistor to determine the TCR and to generate the specific thermal stress desired during testing.  With a closed-loop controller, maintaining the voltage constant for both the thermistor and the resistor is possible.

### 1. General Characteristics

Figure 8 shows the HP 4155B is used to apply a current to the resistor and to the forcing lines of the thermistor.  The voltage at the thermistor sensing pads was measured on each side of the thermistor, and then the difference taken to determine the voltage drop.  For the resistor, the value of the TCR was used to calculate the voltage bias across the resistor (or the current necessary) to produce the desired thermal stress.  No differential voltage was taken directly across the resistor because thermistor resistance was more sensitive and therefore used to calculate bias for the heating resistor.  In order to apply a feedback solution to the heater and thermistor, the differential voltage across the

thermistor sensing pads must be measured while the current is being applied to the heating resistor. Once the current is adjusted to achieve the desired voltage, this voltage will be the reference for the control system. The feedback will use the sensing line to compare the reference signal to the actual differential voltage to measure any difference. Once a difference is detected the comparator can send the difference into the controller, which will make the adjustment to the applied current in order to drive the difference between the reference and detected voltage to zero.

### 2. Specific Solution

Figure 11 shows the specific set up for a control loop that will maintain the voltage across the thermistor and heating resistor constant:

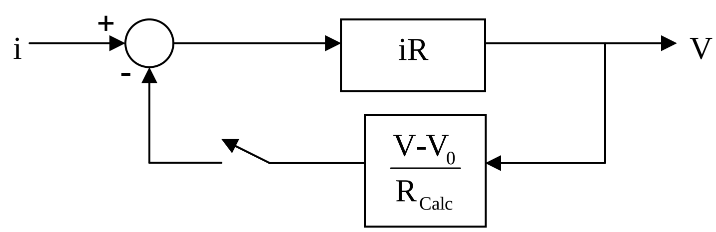


**Figure 11. Specific Feedback Solution.**

The current, i, will be the input into the comparator, represented by the circle. Once the current is applied to the resistor the output voltage (V) will be measured by comparing the differential voltages from the sensing pads of the thermistor at each time interval over the testing period. This voltage measurement will be compared to previous results in order to determine the approximate value of voltage at steady state ($V_0$). Once the voltage has reached a steady state value, this measured value can be entered into the sensing device in the feedback loop, along with the calculated resistance ($R_{Calc}$) value, given a constant applied current and the steady state voltage. At this point the switch on the sensing line can be shut and negative feedback incorporated into the device. The feedback sensing line will have two functions. First, it will receive an input of

the measured voltage from the output. Second, it will calculate the resistance value of the heater given the input current and the output voltage. Initially, the output voltage will be the same as the steady state voltage and the sensing line will provide no feedback.

Over a period of time as the resistance value drifts (either up or down) the calculated resistance value in the sensing line will change with the observed change in the output voltage (input current will remain constant). The value for the reference voltage, previously entered into the sensing line will remain constant. At the next measurement point (depending on the time sequence between the measurements) the input current will be summed with the value from the sensing line to provide a new current through the resistor. This new current will drive the output voltage back towards the originally observed steady state value, and the sensing line contribution to the input will increase or decline as required to maintain this value. The rate of increase or decline will depend on the time interval between measurements and the difference in resistance values between measurements. If excessive ‘hunting’ is observed (a sinusoidal pattern for voltage produced by a series of alternating current corrections) a negative gain can be incorporated into the sensing line to decrease the correction value applied. In the opposite case, if the drift exceeds the correction from the sensing line, a positive gain is applied to curb further resistor change.

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# IV. SOLUTION APPLICATION

## A. HP 4155B

With the theoretical solution determined the method of application to the AFRL test bed must be addressed. Test beds provided by AFRL were unbonded and difficult to work with using Signatone© probes making direct electrical contact with the thermistor pads. Special equipment (such as a pneumatically stabilized test bench and a microscope viewing station) is necessary to take readings directly from the unbonded pads, and variation in the application of probes could produce experimental variation.

Many of these problems are solved with the use of the HP 4155B with the Agilent 16442A test fixture. The fixture has a configuration to test a 28 pin DIP device. By bonding the AFRL test bed to a 28 pin DIP, the Agilent 16442A can be used to relay data to the HP 4155B. The major advantage of using the test fixture is the simplicity and consistency. With the test fixture the 28 pin DIP requires no special stabilization equipment during measurement, and there is no concern for any physical shifting during longer range testing. The 28 pin DIP can be installed and removed quickly from the test fixture, allowing more time for testing the same structure or multiple structures.

The first step is to bond the structure to the 28 pin DIP. Previous research was conducted with four bonded chips, and these bonded structures were used to gather NBTI data. The next consideration is to determine the method and limitations of testing with the HP 4155B.

### 1. Overview of the HP 4155B

The HP 4155B is an instrument designed to measure and analyze the specific characteristics of semiconductor devices. Once the measurements are complete, the instrument is designed for analysis and display of the results [16].

The HP 4155B has four source and monitor units (SMUs) to provide a source for either voltage or current and monitoring capability, two voltage source units (VSUs) to provide voltage bias, and two voltage measurements units (VMUs) to measure bias at a specific point with respect to ground. It has the capability to perform either sweep or sampling measurements [17].

The sweep measurements can be in either linear or log scales, with the start, stop and step sizes defined by the user. After forcing a start value, a hold time between steps can also be defined, as well as a delay time before applying the next forcing value. The sampling measurement is continuous. Voltage or current changes can be monitored for the device under test while forcing constant current, voltage, or pulsed constant bias [17].

In order to do any testing, there are three ways to control the functions of the HP 4155B. The default is to use the HP 4155B with no outside control. There are a number of capabilities pre-programmed into the machine which will meet the needs of most standard testing for semiconductor microelectronics. If the user is attempting to perform a function not available in the pre-loaded menus, the user must then customize instructions to the specific need necessary for the testing. The first method to provide custom instructions can be defined by the user by directly interfacing with the HP 4155B (via keyboard) and programming the test device with Instrument BASIC (IBASIC™). IBASIC™ is the native controller language used by Agilent test equipment to run customized programs. The second method is to use an external computer connected to the HP 4155B with a General Purpose Interface Bus (GPIB). Also known as the IEEE-488 bus, the GPIB was developed by Hewlett Packard to connect testing instruments to computers for further analysis using programs not available on the test equipment. For this experiment the software package Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW©) can be used to take advantage of the visual programming language in order to apply the feedback necessary to the testing. Each method has advantages and disadvantages which will be discussed in detail.

## B. INSTRUMENT BASIC

Instrument BASIC is a way to control Agilent systems directly. The capability is built into the HP 4155B and the equipment has an internal controller aligned for immediate use. IBASIC™ will run a program that controls the HP 4155B and any other test instrumentation connected via interfaces. IBASIC™ is a subset of HP BASIC, therefore any programs in IBASIC™ can run on a HP BASIC controller with little or no modification [18].

### 1. Description and Abilities

#### *a. General Overview*

There are two methods of controlling the HP 4155B with IBASIC™: using an external computer with a GPIB card or using the built-in IBASIC™ controller. After choosing one of these methods, the user must then select the command mode in order to execute the desired program. The first mode is the Standard Commands for Programmable Instruments (SCPI) command mode. The default mode for the HP 4155B, the user can control all of the functions of the HP 4155B and attached equipment during testing. The second choice is the Fast Language for Execution (FLEX) command mode. The user controls only the measurement functions of the HP 4155B in this mode. The advantage of the FLEX mode is the increased speed over the SCPI mode. Finally, the user can choose the syntax command mode. This mode was incorporated to run programs from the HP 4145A/B on the newer test equipment without modification [18].

With the method of control and the command mode selected, the user can begin programming. Mode selections allow all programming to be accomplished with the softkeys available on the face of the instrument, or with an external keyboard plugged into the machine. A help function is available for standard IBASIC™ commands, as well as standard SCPI commands and SPCI commands available only for the HP 4155B [18].

The challenge is to create a program that has the ability to measure the voltage across the heating resistor and make changes to the current applied in order to keep the voltage drop constant. Specifically, the program will provide instruction to the HP 4155B to apply a constant current across the heating resistor via one of the SMUs, read the voltage drop across the thermistor with the VMUs, calculate any change in resistance due to drift, and adjust the applied current accordingly. Because the FLEX mode only allows control of the measurement functions, all programming needs to be in the SCPI mode. The SCPI mode has the ability to set all desired parameters and execute the program in the order desired to achieve the measurement as well as the updated corrections during the applied thermal stress. The basic approach is explained below.

#### *b. Programming Concerns*

In order to program the HP 4155B to perform the measurement scenario it is necessary to understand the set-up, execution and data transfer operations necessary to accomplish the overall task. The first part of the measurement program is the initial set-up. To program a set of initial conditions for a measurement scenario, the SCPI commands can be used to set up the individual screens (menus) inside the HP 4155B to perform the basic tasks. There are three different ways to perform these tasks. First, data for measurements or voltage/current stress can be loaded from a disk, a central server, or internal memory and directly used in the scenario. This is accomplished with SCPI programming to create previously defined and stored routines that will be called in the measurement scenario. Second, data can be loaded as described previously, but the data is manipulated before the measurement scenario is initiated. Third, all of the settings can be defined by SCPI programming in the measurement sequence without loading any previously defined data. The set-up includes assigning an input/output path to control the HP 4155B (either via an external controller using a GPIB cable or the internal

IBASIC™ controller), setting the mass storage device the HP 4155B will reference in any load/save commands, loading previously defined data, and making any changes prior to executing the measurement scenario [18]. A summary of the commands to change various set-up parameters is shown in Figure 12.

| Setup Screen | Command Subsystem |
| --- | --- |
| CHANNELS: CHANNEL DEFINITION | :PAGE:CHANnels[:CDEFinition] |
| CHANNELS: USER FUNCTION DEFINITION | :PAGE:CHANnels:UFUNction |
| CHANNELS: USER VARIABLE DEFINITION | :PAGE:CHANnels:UVARiable |
| MEASURE: SWEEP SETUP | :PAGE: MEASure[:SWEep] |
| MEASURE: SAMPLING SETUP | :PAGE:MEASure[:SAMPling |
| MEASURE: PGU SETUP | :PAGE:MEASure:PGUSetup |
| MEASURE: MEASURE SETUP | :PAGE:MEASure:PGUSetup |
| MEASURE: OUTPUT SEQUENCE | :PAGE:MEASure:PGUSetup |
| DISPLAY: DISPLAY SETUP | :PAGE:DISPlay[:SETup] |
| DISPLAY: ANALYSIS SETUP | :PAGE:DISPlay:ANALysis |
| STRESS: CHANNEL DEFINITION | :PAGE:STRess[:CDEFinition] |
| STRESS: STRESS SETUP | :PAGE:STRess:SETup |

**Figure 12. Summary of Setup Screens for the HP 4155B [From 18].**

With loaded Setup values the measurement execution can begin. A measurement is executed with the ':PAGE:SCONtrol[:MEASurement]:SINGle' command to the HP 4155B in the body of the main SCPI program. The ':REPeat' ending (vice 'SING') is used to repeat a measurement, and the ':APPend' ending is used to append a measurement. The HP 4155B has the

ability to execute either a sweep or sampling measurement. The execution phase is also where the current stress is applied to the heating resistor. With the ':PAGE:SCONtrol:STRess[STARt]' command, the stress is applied from the pre-loaded source or from the previously defined stress in the program memory [18].

The final data manipulation requirement in the measurement scenario is the data transfer option. In the setup phase it may be necessary to load previously stored programs in order to set initial conditions for measurement parameters or applied stress. The programmer must first specify the storage device in use with the ':MMEMory:DESTination' command. Setup data is then loaded with the ':MMEMory:LOAD:STATe command, and measurement data with the ':TRACe' command (vice the 'STATe' command) at the end of the load sequence. Setup and measurement data is stored in the same way (same third parameter), but using the 'MMEMory:STORe:' sequence for storage [18].

### 2. Issues Encountered

A basic programming approach is now possible using the general guidance explained above. Figure 13 shows a basic flow chart for programming the sequence of events. There are a few notable details concerning the setup and flow of data collection. Once the initial test gear set up is accomplished the bias is applied across the heater and the change in voltage (ΔV) is measured. In the previous research it was noted that the heater did not reach a steady state value until about 1000 seconds into the testing [8]. Therefore, a time interval needs to be selected based on previous work as a starting point to choose a steady state ΔV to use as a baseline value. This time delay will allow the heater to reach steady state. Once this baseline is established NBTI measurements can be recorded at the steady thermal stress.

A second consideration is the comparison between the most current ΔV and the pre-recorded steady state ΔV. If there is a change between the values a correction current bias will be applied in order to bring the most recent ΔV back to the steady state value. There are several issues with this correction. First, a

maximum difference must be established for comparison between the two voltage differences. The range must be small enough to ensure the applied thermal stress is within NBTI testing tolerance, but large enough to prevent unnecessary current correction and hunting. Second, when the correction bias it applied the most recent measurements will have to be discarded and the heater ΔV returned to acceptable tolerance before measurements can resume.

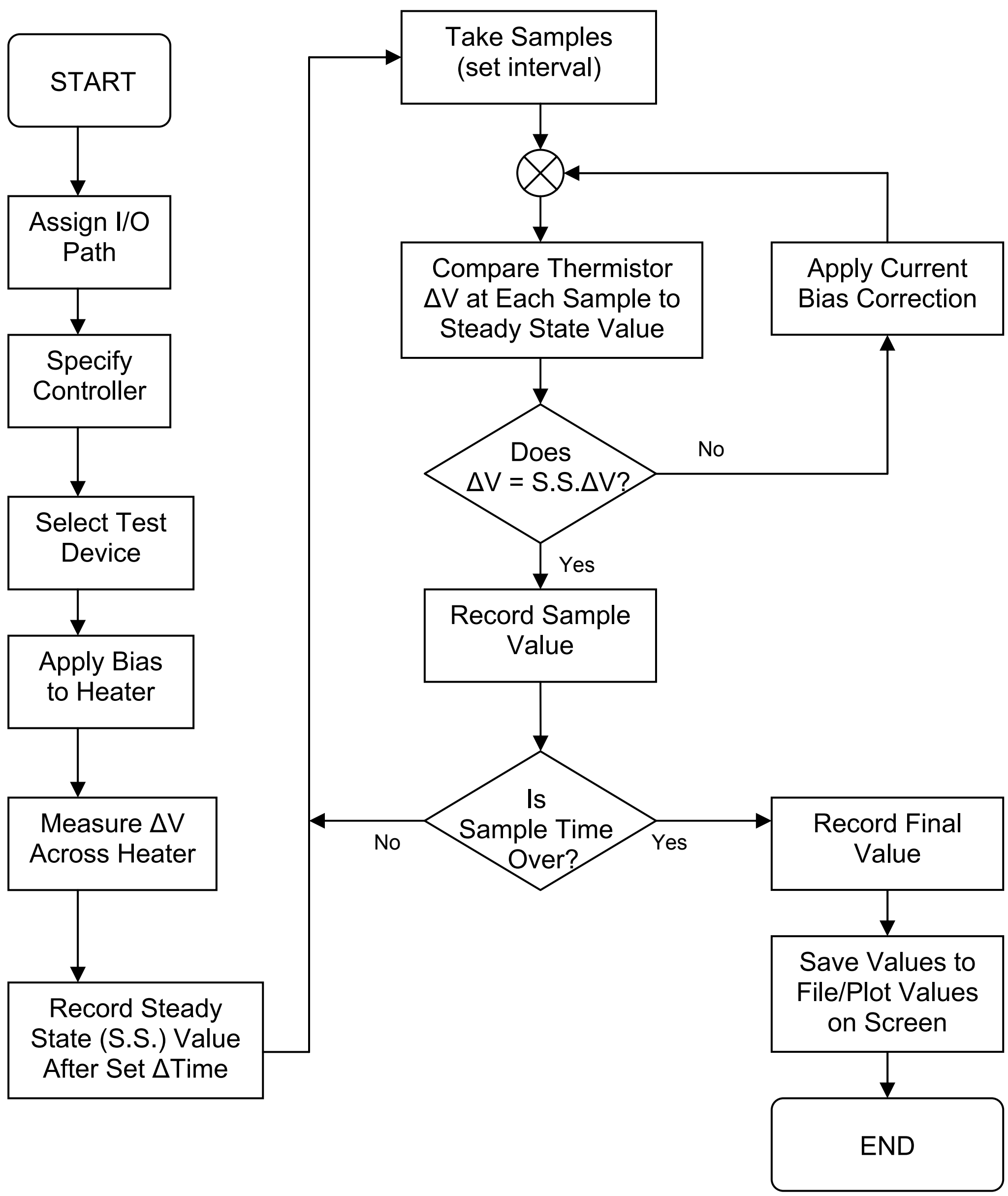


**Figure 13. Programming Flow Chart**

The major drawbacks with the IBASIC approach are the lack of knowledge of the programming language and the reduced flexibility in combining the NBTI measurements with the temperature feedback mechanism. The primary difficulty in the IBASIC approach is becoming practiced enough with the language to construct a program which will perform the desired functions. Preliminary work indicated a program with approximately 200 to 400 lines of code would be necessary to set up conditions simply to control the thermal stress condition of the testing. No consideration was given to the additional programming necessary to conduct the NBTI experiments. While the programming could be conducted in a simulated controller, the assignment of variables and paths to the HP 4155B would require more time to establish. Once the program was operational, testing would include multiple test runs over longer time periods to establish intervals for time to steady state, differences between voltage changes and delays after applying bias corrections. These changes would have to be incorporated into the source code, which would then need to be reloaded to the HP 4155B for further testing. Also, any follow on research would be required to work in the established IBASIC™ testing frame, which could prove difficult to understand. Because of the initial programming time required, lack of flexibility in changes, and the non-integration of the NBTI portion of the testing, the IBASIC™ approach was not used in this research.

## C. LABVIEW©

A much more user friendly method of controlling the HP 4155B was with the use of LabVIEW©. LabVIEW© has a variety of applications that are specific to each device under control, and are usually provided by the device manufacturer to ease programming concerns and allow the user maximum flexibility in the use of the instrument.

### 1. Overview

LabVIEW© requires an external processor capable of running the main program with a GPIB interface to give commands to the device being controlled. The processor must be connected to the device and communication is established either with equipment specific drivers provided by manufacturers or code written specifically to interface the processor to the test device. Once the test equipment is verified to be under external control, a program written in LabVIEW© will control the device.

Using a visual programming medium LabVIEW© provides a wide variety of standard icons to perform specific functions within the overall program. By selecting a specific icon the user can then 'drag and drop' the icon into a workspace. Icons are then interconnected, or 'wired', in the virtual environment. The selection of icons and the order of connection will determine the tasks the testing device is to perform.

To provide the user with a simple environment to enter testing conditions and monitor program progress, a virtual instrument is constructed in parallel with the icon driven workspace. This virtual instrument provides an interface where the user can enter initial conditions, monitor progress, show testing conditions and output graphs or charts during and after data collection is complete and these changes are incorporated into the program. Data can be saved to a file and then transferred to another program for analysis. The advantage of the virtual instrument is the user can change conditions of the testing without the need to enter the programming space and make changes to the internals of the program. When different testing is desired, or different initial conditions require change, the virtual instrument can be changed to reflect the needs of the user. This allows a variety of testing under different conditions by only adjusting the face of the virtual instrument before the test run starts.

### 2. Application for the HP 4155B

The HP 4155B had a variety of features that made programming in LabVIEW© advantageous. First, connection between the processor and the HP 4155B was made simple with an interface on the HP 4155B previously designed for the GPIB hardware and connector cable. Second, Agilent technologies provided the drivers and a selection of instrument specific LabVIEW© applications to streamline programming efforts. This saved a huge amount of time by enabling the user to incorporate these previously programmed standard instrument capabilities into the main testing program very efficiently. Finally, the HP 4155B could be initialized in the local mode and then controlled by LabVIEW© for the experimental run. This again saved programming time because the testing program did not have to set initial instrument parameters, but simply look for the established conditions and control the operation of the device while testing was in progress.

### 3. Experimental Setup

After establishing connection between the processor and the HP 4155B, LabVIEW© was used to program the instrument. The initial conditions were established in the local mode and then the HP 4155B was controlled by LabVIEW© for the duration of the testing.

In order to hold the thermal stress constant during NBTI testing, the initial concept was to incorporate current feedback into the HP 4155B during NBTI testing. After discussions with Agilent technical support and with various independent testing a critical limitation of the HP 4155B was discovered. The machine does not have the capability to alter any parameters during the course of testing. This means any necessary feedback cannot be incorporated into the heater while the test run is in progress.

To overcome this limitation, the next best option is to program the HP 4155B to run a series of shorter tests, and to evaluate/adjust the feedback

current between the test runs. This option is not as desirable as a single, continuous test run, but has the advantage of adjusting the update times as necessary during the testing. If, for example, an eight hour test run is desired, testing intervals could be broken into a series of 24 runs of 20 minutes each. In between each 20 minute interval the temperature of the heater (determined by voltage differential across the thermistor and the pre-determined TCR) would be evaluated and current adjusted accordingly in order to maintain a constant thermal stress.

### *a. HP 4155B Initial Setup*

The first step in the process is to establish the initial HP 4155B setup for applying the current and measuring the feedback. Figure 14 shows the initial setup screen in concept testing.

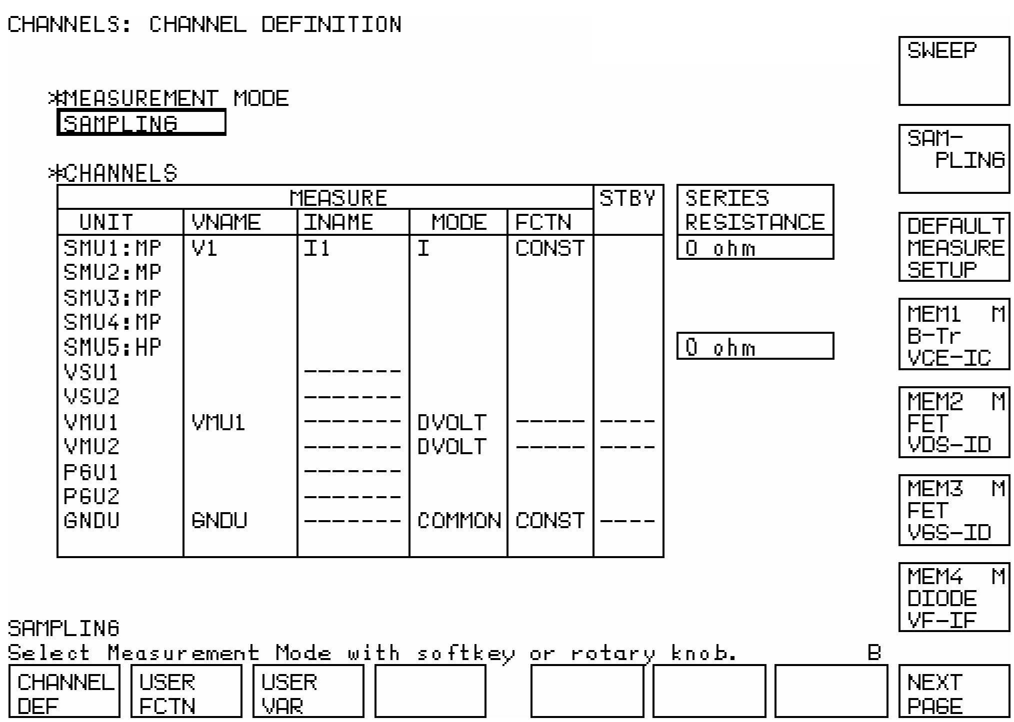


**Figure 14. HP 4155B Channel Definition Screen**

The ‘MEASUREMENT MODE’ field will be sampling to collect the data at constant test conditions. The ‘CHANNELS’ fields will be set to apply the desired stress and measure the differential voltage across the resistor. Current will be applied via SMU1 in the “I” mode at a constant value. The voltage difference is monitored with VMU1 and VMU2 in the differential voltage (DVOLT) mode. The Ground Detection Unit (GNDU) provides both a zero voltage reference value and a sink for the current to complete the circuit through the resistor. Figure 15 shows the second initial conditions screen. This is the screen where testing interval and initial stress conditions are established. In the ‘SAMPLING PARAMETERS’ section the fields are as follows. The ‘MODE’ remains linear to stay consistent with the sampling mode established on the Channel Definition screen. The ‘INITIAL INTERVAL’ is the interval between samples. Because the time to sample is on the order of one millisecond, any interval above 10 milliseconds will be satisfactory for testing. ‘NO. OF SAMPLES’ works with initial interval to establish the total sample time in the automatic mode (shown below), or the total sample time can be set manually (not recommended). The ‘HOLD TIME’ is the amount of time that test conditions will be applied before sampling begins. ‘FILTER’ set to ‘ON’ reduces the amount of peripheral circuit noise encountered while sampling. ‘STOP CONDITIONS’ are not used in this testing. In the ‘CONSTANT’ section, UNIT, NAME, and MODE are defined on the Channel Definition page. The ‘SOURCE’ field defines the initial current stress applied to the heater, and the ‘COMPLIANCE’ field sets the maximum voltage the HP 4155B will record in the measurement mode. Because the VMU differential voltage mode will be used, the maximum compliance is two volts [17].

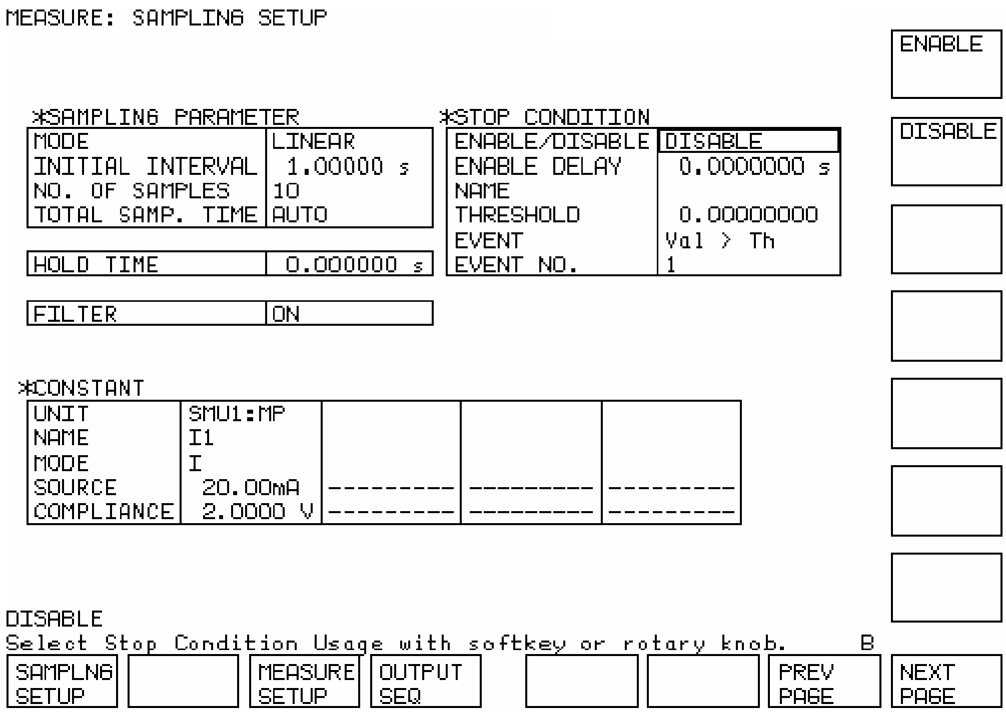


**Figure 15. HP 4155B Sampling Setup Screen**

### *b. LabVIEW© Programming*

With the initial conditions established on the HP 4155B, LabVIEW© can now be configured to take over the operation of the device and run the desired testing. As stated earlier, it is beyond the capability of the HP 4155B to update while testing, so a program with shorter testing periods is necessary to measure the differential voltage across the heater, evaluate this data for change, and adjust the applied current accordingly in order to maintain the thermal stress constant.

The first step in the program is to provide an input for initial current stress conditions and voltage compliances, as well as set the HP 4155B mode and begin the sampling. Figure 16 shows the initial setup.

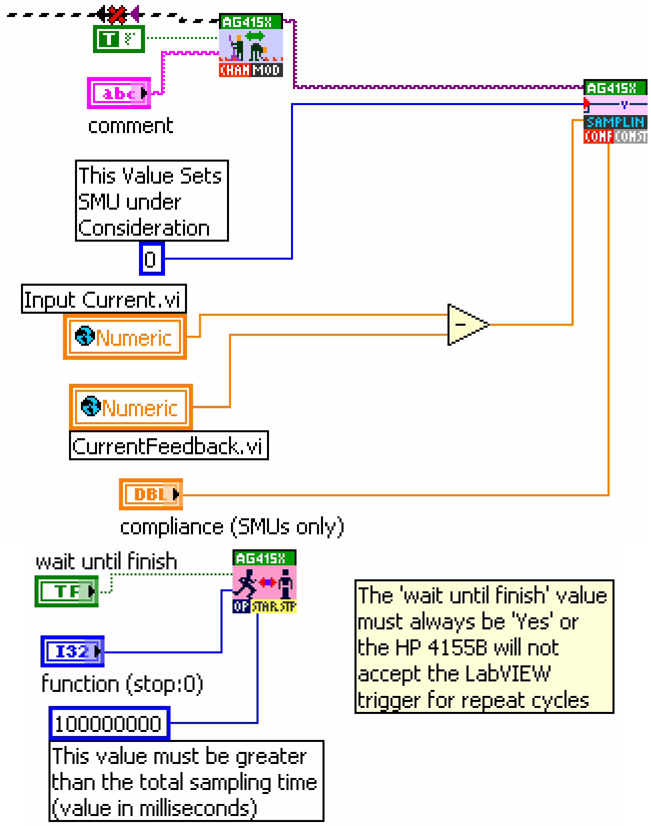


**Figure 16. HP 4155B LabVIEW© Initial Setup**

The global variables (denoted by the globe icon in front of the 'Numeric' term) are used to update values throughout the LabVIEW© program at any location, whenever they are changed. The other parameters are set to establish the instrument initialization that was not previously established in the local mode. The three blocks with the green band on the top are Agilent provided subroutines programmed specifically for the HP 4155B to perform certain functions. The programming is represented by the following Virtual Instrument (VI) shown in Figure 17. The source (current) and compliance can be entered on this VI, as well as the function of the instrument. Display values (trace values, Current Feedback Value and Vactual-Vreference) will be discussed with Figure 18.

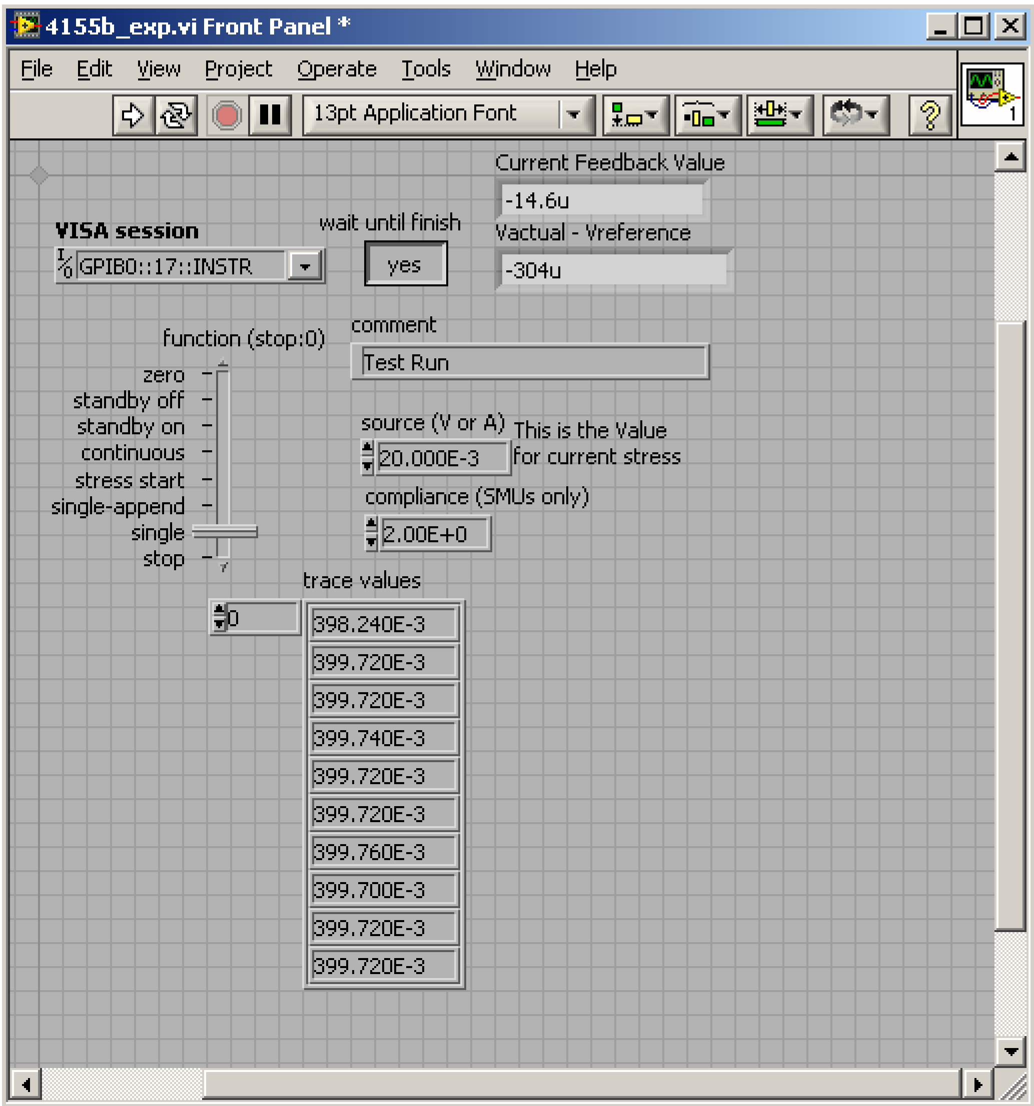


**Figure 17. HP 4155B LabVIEW© Virtual Instrument for Current Feedback**

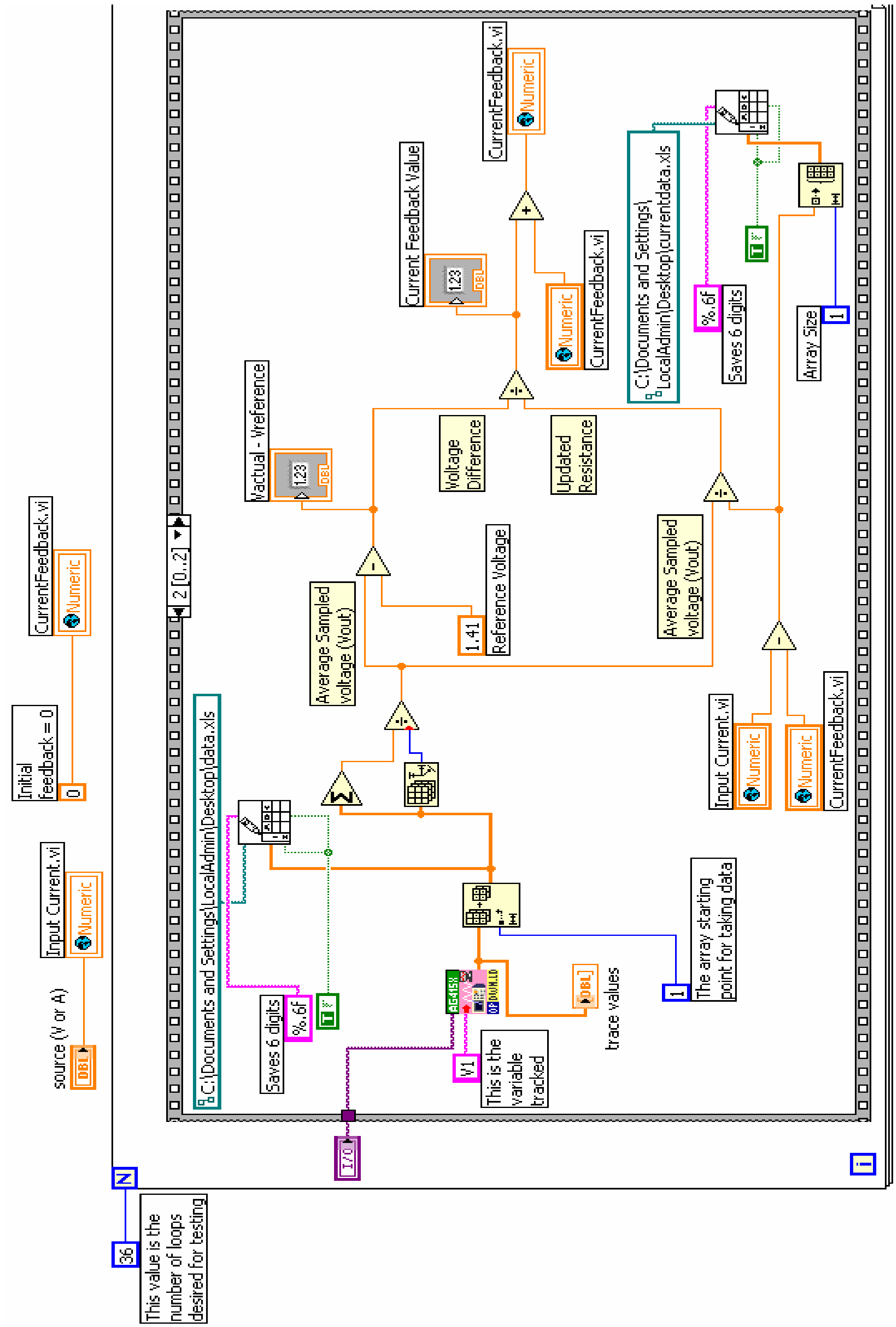


**Figure 18. HP 4155B LabVIEW© Current Feedback Controller**

The final portion of the LabVIEW© program deals with the collection of the most recent test data, calculation of the differential voltage, adjustment and application of the feedback current, and commencement of the next testing cycle. Once the test cycle commences, the data is collected in an array within the HP 4155B. Upon conclusion of the test the differential voltage sample points are transferred into a LabVIEW© buffer. The initial data point is truncated as the beginning of the test to this point is the interval where the HP 4155B ramps up the applied current from zero amps to the desired test level. Because this data point is not at a constant value it is of no use for analysis and is therefore discarded. After this point, the data is saved in a file and all subsequent data from later runs is appended to the same file (sans the first value) for later analysis.

The differential voltage data is then averaged to determine an average differential voltage value over the testing period. This most recent differential voltage value is then used in two separate analyses. The first is a comparison to the reference differential voltage that was found in baseline testing. This baseline voltage is taken from each individual AFRL device to capture the exact parameters of the heater in use for that particular device. This also determines the amount of differential voltage necessary to provide the thermal stress desired for testing. The value for the reference voltage is entered into the program, and the difference between the most recent differential voltage and the reference differential voltage will determine the amount of current feedback necessary. While previous testing theory in IBASIC™ advocated a waiting period to steady state, this value can be entered at the beginning of testing and no delay is necessary before data collection begins.

The second place the most recent differential voltage value is used is when determining the most recent resistance value. Because the resistance drifts over long periods of testing, the value of resistance must be re-calculated to compensate for the drift. By taking the initial input current and the feedback value (summed in a negative feedback loop), the total applied current is

available.  The most recent differential voltage is then divided by the total applied current to give the value of the resistance after the most recent test run.

With the difference between the actual and reference differential voltage and the most recent resistance value, a feedback current value can be calculated.  This feedback value is then added to the last feedback value to provide a running total of feedback current necessary to apply at the beginning of the next NBTI testing cycle.  The global value of feedback current will update before the next test cycle begins, and the process repeats for the programmed number of cycles until testing is completed.

# V. RESULTS AND CONCLUSIONS

## A. TESTING RESULTS

Once the programming was completed the testing could begin. The first consideration was to test the concept to ensure the LabVIEW© program performed the desired function. Once concept testing was complete and satisfactory additional testing would be conducted on the AFRL test bed.

### 1. Concept Testing

With the LabVIEW© program complete a proof of concept test cycle is conducted. To prove the feedback loop will force differential voltage to the reference value, a variable resistor (a decade box in this case) is used to simulate the heater in the circuit. The differential voltage is taken across the resistance and recorded during the period of measurement. Eight test cycles consisting of 50 samples (one sample taken every 0.1 second for a total of 5 second cycles) were conducted, and resistance was both increased and decreased to demonstrate the capability of the feedback loop. Figure 19 shows the graphical results of the test.

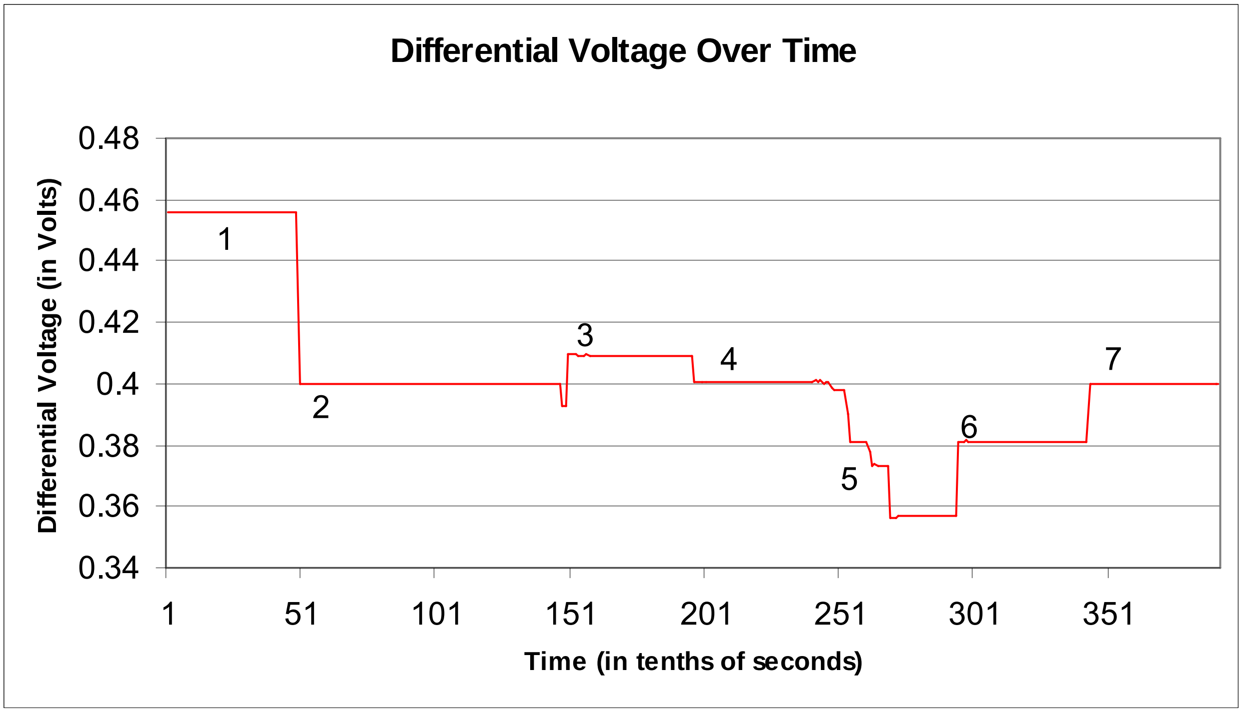


**Figure 19. Data Summary of Test Cycles**

At the beginning of the test cycle heater current is set at 20 milliamps (mA), reference differential voltage is 0.400 volts, and resistance in the decade box is set to 22 ohms (which is measured accurately at 22.80 ohms). The test cycle then commences. The first run returns an expected differential voltage value of 0.456 volts, based on the initial resistance and applied current (point 1). When the first five second period is completed the differential voltage data is evaluated and the differential voltage is forced to the reference value of 0.400 volts by adjusting the applied current to 17.54 mA (point 2). Resistance is not changed for the duration of the second and third cycle to demonstrate current will not change and voltage is maintained at 0.400 volts when resistance remains constant. At the beginning of the fourth cycle resistance is increased to 23 ohms on the decade box (accurately measured at 23.32 ohms) which accounts for the voltage increase to 0.409 volts (point 3). Upon the completion of the fourth cycle the applied current is re-adjusted to 17.21 mA to force the voltage to 0.401 volts

(point 4). The reason voltage is not forced back to exactly 0.400 volts is because the initial 2 to 5 data points are skewed due to the spike on the graph as resistance was changed. At the end of the fifth cycle and in the beginning of the sixth cycle the resistance was moved on the decade box from 23 ohms (23.32 ohms) to 21 ohms (20.78 ohms measured accurately—shown at point 5). This forces the differential voltage for the remainder of the fifth run to be 0.358 volts (between points 5 and 6). At the end of the sixth cycle the current is adjusted to 18.35 mA, which forces the differential voltage to 0.381 volts (point 6). Again, the reason current is not adjusted back to the reference value of 0.400 volts is because all of the differential voltage data in the previous cycle is averaged to give a new differential voltage value, so the change in resistance (and subsequent changes in differential voltages) are included in the average. In the seventh cycle resistance is not varied and at the commencement of the eighth cycle (point 7) the applied current is adjusted to 19.25 mA to force the differential voltage back to the reference value of 0.400 volts.

This concept test demonstrates that should resistance vary during one of the testing cycles, the current applied to the heater will be adjusted accordingly to force the differential voltage back to the reference value. It makes no difference if the resistance is raised or lowered because the control loop accounts for changes in either direction. In this test case the resistance changes were large and sudden, where actual data in extended testing show the temperature drift (resistance drift) to be very gradual over a longer period of time. Because the average of all of the data is taken for the previous cycle, the correction to the applied current will be adjusted to minimize any overshoot and time to steady state. As seen in Figure 9 the temperature drift was on the order of a degree over a period of five hours, so the corrections to applied current will not be drastic or wide ranging from initial applied values.

### 2. Delay Time between Test Runs

With concept testing consisting of a pre-determined number of machine resets, the delay time between testing is an additional fact important to note. In effect, the LabVIEW© program is similar to a user waiting until a testing run is over and cycling the machine manually to begin another test run. Because the thermal stress will be absent from the heater between cycle times, the times need to be noted and compared to the duration of the testing runs.

To accurately determine the time between current stresses to the heater an oscilloscope was connected to each side of the differential voltage monitoring units. While the heater was under current stress the oscilloscope measured a high value, and when the stress was removed the measured value was low. Five series of tests were performed with five series of stresses (which provided four intervals when stress was removed). The test results are shown in Figure 20.

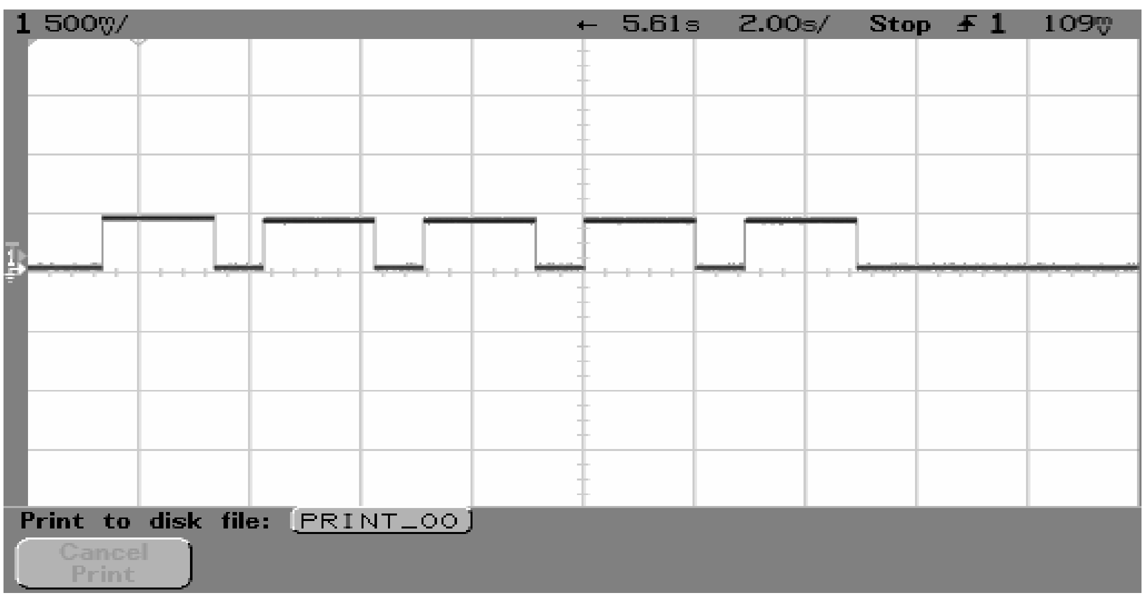


**Figure 20. Typical Testing Series to Determine Cycle Delay**

Each delay period was then examined with a larger scale as shown in Figure 21.

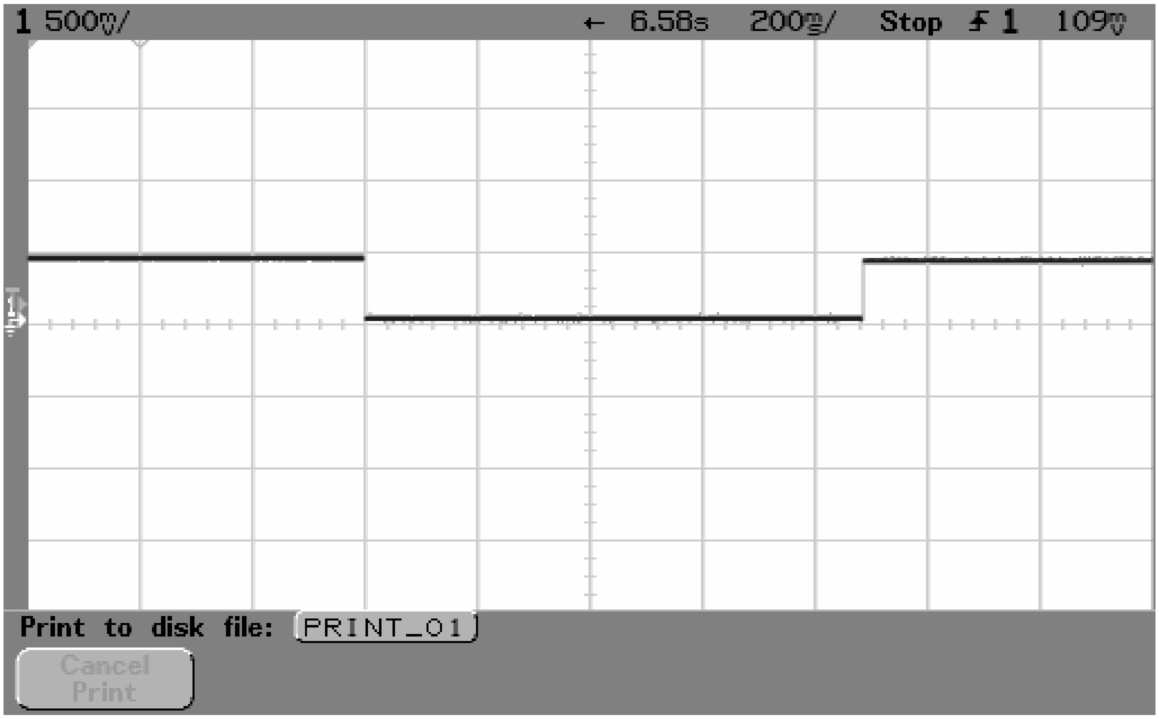


**Figure 21. Cycle Delay For A Single Cycle**

These measurements were then averaged over all tests to determine a working delay time. The results are shown in Table 4. All delay times are in milliseconds.

**Table 4. Delay Measurements**

| | 1st Delay | 2nd Delay | 3rd Delay | 4th Delay |
|---|---|---|---|---|
| Test #1 | 876 | 885 | 888 | 876 |
| Test #2 | 887 | 880 | 878 | 869 |
| Test #3 | 881 | 876 | 889 | 872 |
| Test #4 | 892 | 873 | 881 | 884 |
| Average Delay | 880.44 ms. | | | |

This delay value is important when examining the testing cycle under consideration. With a testing cycle of 10 seconds or less, the delay time between cycles is a significant percentage of the total, and the heater is without stress for that time. However, when testing cycles are on the order of five to twenty minutes the delay time is a very small percentage of the total testing time and the amount of time the heater is without current stress is deemed negligible during the course of the overall test.

### 3. AFRL Test Device Testing

With the concept testing completed and the delay time known, the AFRL testing device is placed under test. Using the test setup shown in Figure 8 the device was put under test. From Table 3 a value of 1.41 volts (correlating to approximately 75 degrees Celsius) across the thermistor was selected for the reference voltages in the testing cycles. The resistance of the heater was measured to determine the specific heater current required to create a differential voltage across the heater of 1.41 volts. The heater resistance was measured at 22.20 ohms (at room temperature). With this resistance, a current of 63.50 mA will produce the desired differential voltage.

Two tests were conducted, a one hour and an eight hour test. A cycle time of five minutes was selected to allow the heater time to begin to heat up, but not quite reach equilibrium. Sample intervals were set at five seconds apart (for a total of 60 samples per cycle). In the one hour test twelve cycles were used, and 96 cycles in the eight hour test. The following figures show the results of the two tests.

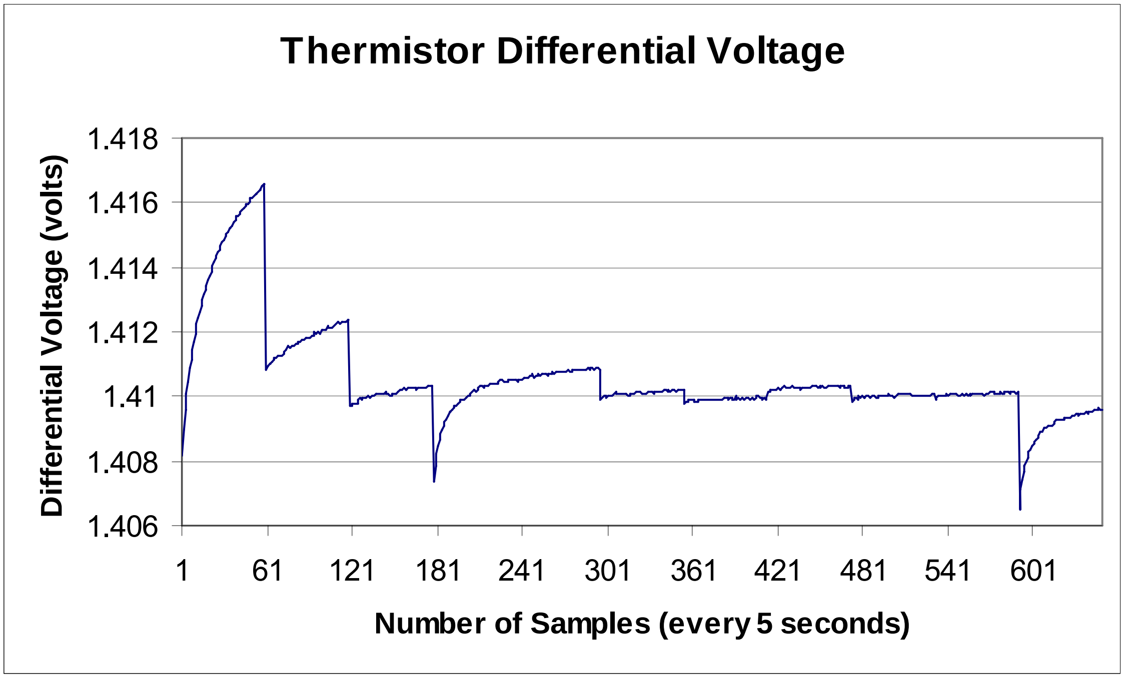


**Figure 22. One Hour Test of Thermistor Differential Voltage**

At the beginning of the stress period the differential voltage rises as the heater (and thermistor) begins to feel the thermal stress. With the end of the cycle the current is adjusted based on the differential voltage values and re-applied. Figure 22 shows the rises of differential voltage grows steadily smaller as the voltage across the resistor is forced to the reference value of 1.41 volts. There was a curious spike noted at the 15 and 45-minute points, but this is simply because the HP 4155B auto calibration feature was not disabled prior to testing, and the calibration time of 20 to 30 seconds allowed the heater to cool before testing resumed.

In order to maintain the voltage constant the current value would decrease upon each application (at the beginning of the test) and then remain relatively constant for the remainder of the cycle. This trend is recorded in Figure 23. The beginning value for current was 63.50 mA for the first five minutes. Upon each re-evaluation, resistance increased and the current was decreased to force differential voltage to the reference value. Because of the limitations of the HP

4155B, this current was only applied at the beginning of each five minute test cycle, which is the reason for the time delay when coming to steady state. If a quicker steady state time is desired, shorter testing cycles are necessary, but this may also increase variation at steady state values.

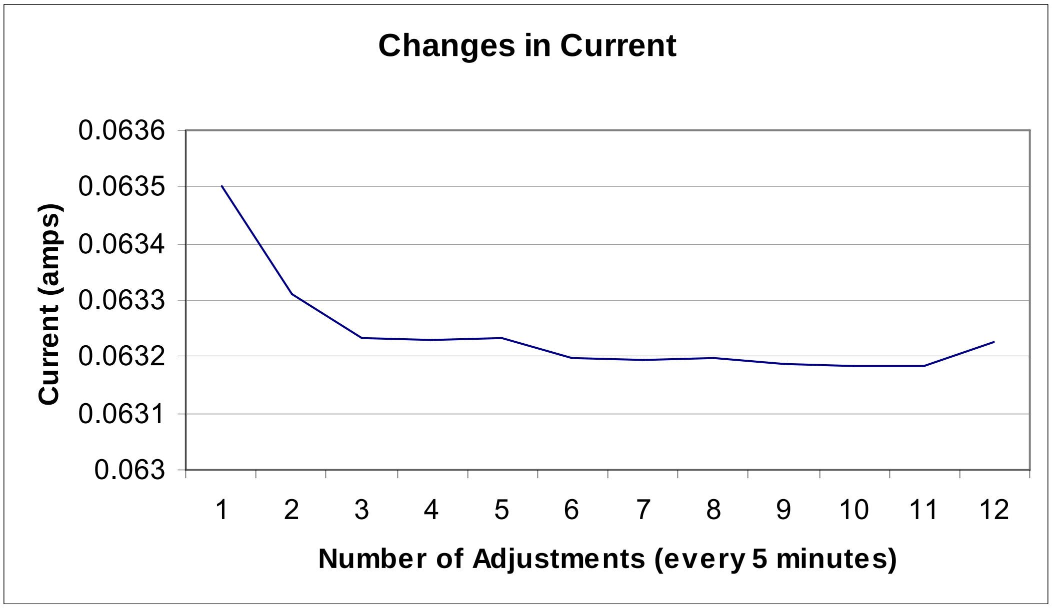


**Figure 23. One Hour Test Heater Current Values**

Eight hour testing followed the same general pattern. Figure 24 shows the thermistor differential voltage over the eight hour testing period. Like the one hour test, the initial values are very high as the resistor receives the initial stress and begins to come to steady state. After approximately ten minutes the differential voltage value is corrected to an approximately steady state value ($\pm$0.004 volts, until approximately 6.4 hours when the differential voltage increased slightly). For the remainder of the test there is some ‘hunting’ noted as the resistor is continually stressed and relaxed, possibly causing thermal changes which would require more or less current, depending on the previous amount of current applied.

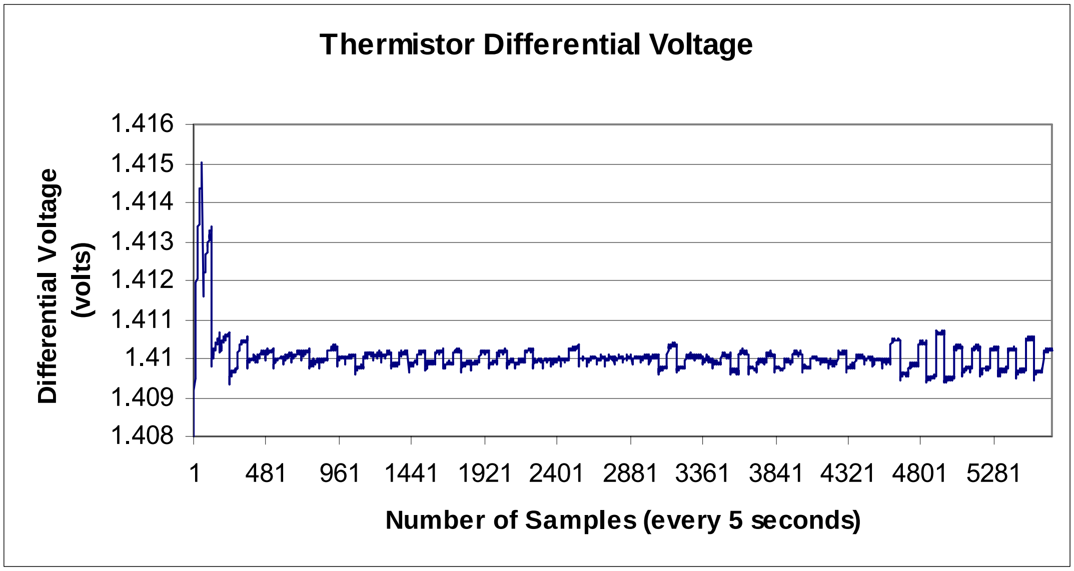


**Figure 24. Eight Hour Test of Thermistor Differential Voltage**

Figure 25 shows the current values over the eight hour testing period. It is interesting to note that after five hours of testing the average current value rises by approximately 50 microamps in order to keep the differential voltage value at steady state. This would suggest either a change in the heat gradient or some sort of current leak-by after a fixed amount of testing.

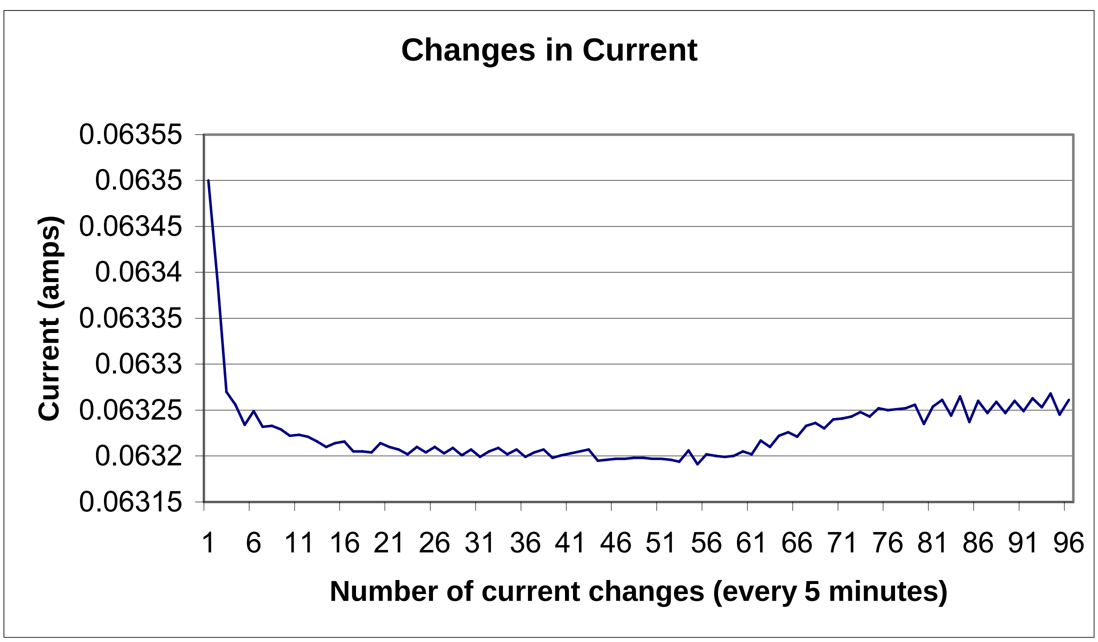


**Figure 25. Eight Hour Test Heater Current Values**

In an attempt to reduce the amount of cyclic variation in the application of current, a longer application period (ten minutes) was attempted with the following results:

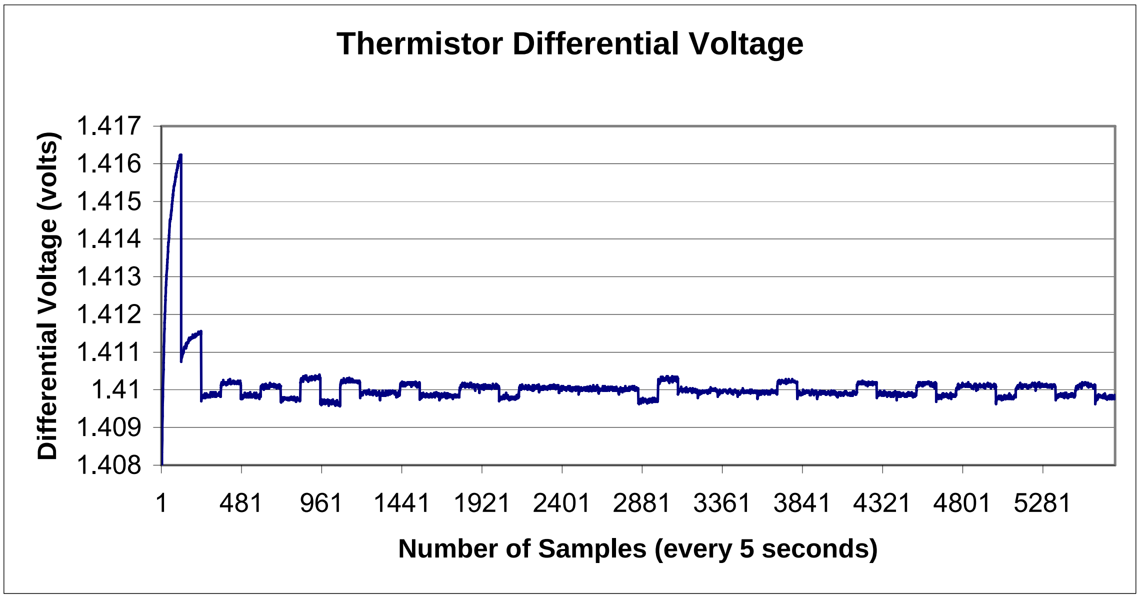


**Figure 26. Eight Hour Test of Thermistor Differential Voltage, 10 Minute Stress Periods**

The cyclic variation is reduced and the amount of difference between the desired value (1.41 volts) and recorded values is on average less than the five minute testing period. This shows that a longer data run allows the AFRL device to reach more of a ‘steady state’ value in each run and the current correction does not need to be as great. Figure 27 shows the current corrections. These corrections more closely match data presented in Figure 9 which displays a gradual decrease in temperature. The heater current changes in Figure 27 show a gradual increase over the testing period, which indicates some change in resistance which would cause differential voltage (and therefore temperature) to fall over the eight hour testing period.

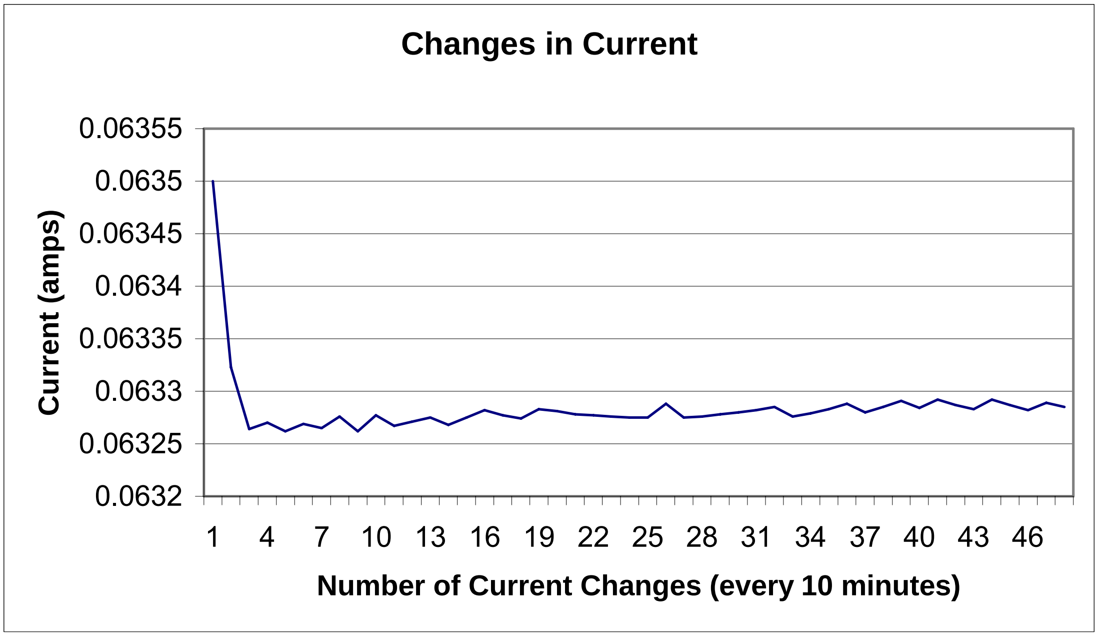


**Figure 27. Eight Hour Test Heater Current Values, 10 Minute Stress Periods**

To find the magnitude of the change in temperature, the previously determined average TCR of 0.0028 [8] is used to calculate the maximum temperature difference that could be expected, given the maximum voltage difference over the period of testing. In Figure 24 the maximum differential voltage recorded after the heater had reached steady state was 0.0013 volts (between samples 4956 and 4957). Using the values found in Table 2 [8] the average change in voltage per degree (averaged between Device A and Device B) is 47.88 degrees Celsius per volt. Which means a change of 0.0013 volts would correlate to a temperature change of 0.062 degrees Celsius. In Figure 26 the maximum voltage change is 0.0007 volts (between samples 952 and 953), which correlates to a temperature change of 0.033 degrees Celsius. In both cases, the temperature is held to approximately 5% of one degree Celsius.

## B. CONCLUSIONS

The current feedback correction is successful in that current is calculated and adjusted as resistance drifts, but the solution is not ideal. Because this

solution requires a longer test to be broken into a series of shorter testing intervals, the device is forced to undergo a cyclic stress and testing profile. While there may be no impact to the device with this application and removal of current to the heater, the experiment data collected from NBTI testing could be skewed due to the cycles.

### 1. LabVIEW© Conclusions

LabVIEW© was very user friendly and made programming intuitive when designing a solution to the current feedback issue. The virtual instrument made altering initial conditions easy and eliminated the need to enter the program to make changes internally. There are a few other values that could be incorporated on to the face of the virtual instrument so all parameters of interest are either displayed during testing or set before the testing cycle begins (reference voltage, for example, must be changed internally in the program). The time between cycles will have minimal impact on the longer testing cycles, but with shorter cycles, it could pose a problem.

The cyclic differential voltage remained very close to original values and, with the previously found TCR, the temperature variation would be less than five percent of one degree Celsius. Should testing require a tighter thermal stress the feedback solution could be altered to account for later data, or take a different portion of differential voltage to perform the average used in the correction calculation.

Because the heater current solution was conducted in LabVIEW© the remainder of the NBTI testing can be incorporated into the heater program. Initial conditions for testing can be set locally, and during testing data can be gathered via LabVIEW© sub-routines which would either display the results or save the data points to a file for further review.

### 2. HP 4155B Conclusions

For the earlier NBTI testing the HP 4155B was a very good choice. With the ability to stress while measuring data the HP 4155B could collect the desired data for analysis. However, with the observed drift in differential voltage across the thermistor, a need to adjust heater current during testing is necessary to maintain a constant thermal stress. The HP 4155B is incapable of making this adjustment during a measurement cycle and must be adjusted and re-started to maintain the thermal stress constant. In the interest of maintaining thermal stress as continuous and constant as possible, the HP 4155B is not the ideal test instrument. Valid test data can be gathered from this instrument, but future research should be conducted with an instrument that has a stress adjustment capability while measurement is underway.

### 3. Areas for Further Study

With the ability to apply a constant thermal stress, the initial testing can be conducted again, and results from both tests compared to determine the impact of the temperature drift. There are also additional areas for further study

#### *a. Initial Temperature Calibration*

The TCR was initially calculated by heating an unbonded AFRL test device on a Hot Chuck heating device. There was no indication that the Hot Chuck was accurately calibrated to deliver the desired temperature, the amount of temperature drift over time, or the temperature variation range over time. Further work to calibrate a heat source would provide a more exact TCR which would lead to a more precise thermal stress requirement to produce a temperature.

#### *b. Control Application*

The control solution is successful in forcing the value of the differential voltage to the desired value, but ‘hunting’ observed in the above plots

shows the control loop may need to be adjusted if closer tolerance is required. Possibly the time interval for data collection could be changed, or the number of differential voltage values used in the calculation of the feedback current. Tolerance could be reduced to ranges desired, but it may be difficult to incorporate a single control solution to a device under test that needs to initially come to equilibrium under stress, and is then cycled for the remainder of testing.

#### *c. Feedback Verification*

Temperature feedback was verified to remain within 5% of one degree Celsius, but impact on the actual PMOS component was not shown. A record of diode gate-drain voltage over the stress period would show any changes with thermal stress, which would indicate that thermal stress change is still great enough to impact the device under test. Further programming in LabVIEW© to record this data and plot over time could be used to verify the effectiveness of the feedback loop.

#### *d. Further NBTI Testing with Integrated Heater Control*

NBTI testing can be continued with a constant thermal stress. The tests in question were the long term tests at 25 and 100 degrees Celsius for periods of three hours and beyond. By breaking up the testing into shorter cycles data could be gathered with the thermal stress constant and compared to the previous data to determine changes (if any). An important part of this testing would be to determine if the cyclic effect on stresses had any effect on the NBTI data. A control run could be performed using the previous methods and additional testing using the cyclic approach for comparison. In addition, the Charge Pumping or Direct Threshold Voltage Measurement could be attempted and the results compared to previous research without and with temperature feedback.

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